NASA TECHNICAL TRANSLATION NASA TT F-15,776

SPACE TELEVISION (QUESTIONS OF THEORY AND PRACTICE OF SPACE TELEVISION SYSTEM DESIGN)

P. F. Bratslavets, I. A. Rosselevich, and L. I. Khromov

Translation of Kosmicheskoye Televidiniye,
"Svyaz" Press, Moscow, 1973, 248 pp.
(2d Edition, Supplemented)

(NASA-TT-F-15776) SPACE TELEVISION: QUESTIONS OF THEORY AND PRACTICE OF SPACE TELEVISION SYSTEM DESIGN (Kanner (Leo) Associates) 251 p HC $15.75

N74-32606

CSCL 09F G3/07

Unclas 48445

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D. C. 20546 September, 1974

STANDARD TITLE PAGE

1. Report No. NASA TT F-15,776
2. Government Accession No.
3. Recipient's Catalog No.
4. Title and Subtitle SPACE TELEVISION (QUESTIONS OF THEORY AND PRACTICE OF SPACE TELE-VISION SYSTEM DESIGN)
5. Report Date September, 1974
6. Performing Organization Code

7. Author(s) P. F. Bratslavets, I. A. Rosselevich, and L. I. Khromov

8. Performing Organization Report No.
10. Work Unit No.
11. Contract or Grant No. NASw-2481

9. Performing Organization Name and Address
Leo Kanner Associates
Redwood City, California 94063

13. Type of Report and Period Covered
Translation

12. Sponsoring Agency Name and Address
National Aeronautics and Space Administration, Washington, D.C.20546

14. Sponsoring Agency Code

15. Supplementary Notes
Translation of "Kosmicheskoye Televideniye", "Svyaz" Press, Moscow, 1973, 248 pp. (2d Edition, Supplemented)

16. Abstract
Information is given on television for space research, including definitions, fields of use and classification of space television systems, structural diagrams, video signal formation, amplitude-frequency characteristics, system feasibility conditions, television parameter selection and the effect of linear and noise characteristics on image quality. Fundamentals of television theory are presented, including general information, discrete and continuous communication systems, receivers, including theory of continuous reception, potential resolution and the optimum television camera. Slow-scan transmission of television data from space is presented, including television signal spectrum compression, memory length, camera tube storage, slow-scan video signal formation, television camera light sensitivity, camera tube target erasure, storage and counting in field control mode, video preamplifier and video signal processing in the intermediate video amplifier. The light television, narrow-band mechanical, narrow-band electronic and wide-band electronic systems are discussed.

17. Key Words (Selected by Author(s))

18. Distribution Statement
Unclassified-Unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	243	

NASA-HQ

ANNOTATION

Questions of theory and practice in design of space television systems are examined. On the basis of information theory, a theory of a space television system is developed. Method of calculation of the principal television parameters is reported. Prospects of solution of television problems are discussed: increasing transmission distance, increasing sensitivity and resolving power of systems. A description of modern space television systems is given.

The book is intended for scientific and engineering-technical workers, occupied with creation and operation of television systems, as well as for students and graduate students in the appropriate specialties.

ABOUT THE AUTHORS

The authors set themselves the task of reporting the specifics of space television, in the theoretical and engineering aspects. In writing the book, the authors were guided by the desire to assist space television system designers in discussing complicated questions of optimization of a television set and its "heart," the onboard apparatus.

The book is intended for readers familiar with the path of television [1,2]. Familiarity of the reader also is assumed with the general problems of communications theory, for example, according to textbook [3]. In setting forth the foundations of the theory of optimum reception and information theory, the authors extensively use the premises in the basic works of the V. A. Kotel'nikov, A. N. Kolmogorov, K.Shannon and N. Viner [4-7].

A definition of space television is given in Chap. 1 and one of the most advisable versions of classification of space television systems is presented. Possible fields of use of television in space research are pointed out. The basic qualitative television characteristics and the specifics of planning a space television system are discussed.

The results of development of television theory, based on the theory of optimum reception and information theory are reported in Chap. 2, in the interests of formalization of the process of planning optimum space television systems. New results, concerning solution of the problem of digitization of continuous communications, may be of interest beyond the framework of television. A television camera is considered as a device, the planning of which must be carried out on the basis of theory of the optimum receiver of continuous information.

The fundamentals of the slow-scan method of image transmission are reported in Chap. 3; this permits, on the contemporary engineering level, solution of the problem of compression of the video frequency band (increasing the distance of television transmission) and increasing light sensitivity and resolving power of the system. The results of achievements in this major area of space television technology are presented.

A brief description of a space television system, predominantly domestic, is presented in Chaps. 4 and 5, as illustrations of the positions developed in the book.

Original material contained in the book is based on articles of the authors published in various publications.

Chapter 1, except for section 1.5, sections 3.1, 4.2 and 4.3, were written by I. A. Rosselevich; Chapter 2, sections 3.2, 3.3, 3.5 and 3.6, by L. I. Khromov; sections 4.1 and 4.4 and Chapter 5, by P. F. Bratslavets; section 3.4 was written jointly by P. G. Bratslavets and L. I. Khromov; section 1.5, jointly by I. A. Rosselevich and L. I. Khromov.

At the request of the authors, section 3.7 was written by O. I. Fantikov and section 3.8, by T. I. Tayts.

In preparation of the book materials, V. I. Konchin, V. I. Resin, L. A. Litvinchuk, B. I. Reznikov, G. A. Sushchev and M. I. Tovbin gave assistance to the authors on individual questions.

I. L. Valik and S. P. Pivovarov looked through the manuscript of the book.

The authors thank all these persons and express deep thanks to S. I. Katayev and P. V. Shmakov, for supporting the initiative of publication of this work and for valuable advice.

Responses by the readers should be directed to the Svyaz Press (Moskva-tsentr, Chistoprudnyy Bul'var, 2).

FOREWORD

Fifteen years have passed since the historical event, the launching of the first artificial earth satellite in our country. The past years have been years of formation and vigorous development of space technology, which proved to be a revolutionizing influence on all the principal branches of industry. The building of spacecraft returnable to earth and nonreturnable, the creation of manned spacecraft required development of complicated radio engineering sets, providing for control of spacecraft and their functioning. One of the highest achievements of domestic space radioelectronics is space television. Under ground conditions, in the conduct of scientific radar research, owing to its all-weather nature, and photography, owing to high definition of photos, successfully compete with television. Transfer of a scientific experiment to space makes television means dominant. This is particularly graphically clear in the example of moon and planetary studies, by means of nonreturnable spacecraft, when photography is inapplicable and television is the only accessible method of observation of space objects in the form of images. Therefore, it is not surprising that, two years all told after the first artificial earth satellite, the Luna-3 Spacecraft was launched; its primary function consisted of using slow-scan television to obtain television photos of the back side of the moon. At the present time, slow-scan television systems have become a major portion of many spacecraft intended for study of the moon and the planets.

Equipping manned spacecraft with television has developed no less intensively. In the performance of official functions in spacecraft, television technology is not limited to video monitoring of the astronauts, which predominated in the first stage of development of space television. A television system is more extensively included directly in the command circuits of spacecraft, providing for their orientation and transmission of video-telemetric data.

Slow scan television was the most efficient means of observation of cloud cover and the surface of the earth in the interests of meteorology. Perfection of these systems permits more extensive monitoring functions to be carried out on the natural resources of the earth, in the interests of the entire national economy.

Small-size onboard equipment, severe operating conditions, in combination with requirements for high reliability, have stimulated development of space television technology as a specific branch of television. However, space research has given birth to, not only technological and design specifics of space television systems, in contrast with television broadcast systems. A considerable group of problems in space research would have been solved in a nonoptimum manner or generally could not have been solved, within the framework of the standard broadcast television GOST[1] 7845-55, because of its nonconformity with the characteristics of the objects observed and the transmission distance. The selection of television parameters of a planned system, in conformance with the characteristics of the object observed, illumination conditions and distance of communications, are specific for slow-scan space television.

The requirements of space research cannot be satisfied without solution of the basic problems of space television: the problems of sharp increase in television transmission distance and the problems of achieving maximum light sensitivity. These problems, in combination with the high cost of each bit of television data from space, served as a powerful stimulus, not only towards perfection of the equipment fabrication technology, but towards creation of a theory, providing space television system planners with a method of synthesis of an optimum system. Development of this theory turned out to be possible, thanks to drawing on the theory of optimum reception of V. A. Kotel'nikov and information theory, developed for the case of continuous signals, of A. N. Kolmogorov. In this theory, the onboard television camera is considered as an optimum receiver of the images of space objects in the optical wavelength range. This approach permits, not only optimization of the television system, but it has the necessary generality for complexing the onboard television devices with other radioelectronic sensors and, mainly, with the radar system. The television and radar equipment emerge as a single system for collection of videoinformation in various electromagnetic wavelength ranges aboard spacecraft.

The first edition of this book came out eight years after the launch of the first space television system and, speaking figuratively, it consequently was written "hot on its heels." The book secured the domestic priority in development of space television, and it had a deserved success. In the second edition, the authors have preserved the structure of the book and the subject matter of the chapters, but they have supplemented it significantly with new material, previously reported only in the journals.

V. Nemtsov

[1][GOST--All-Union State Standard.]

TABLE OF CONTENTS

SPACE TELEVISION (QUESTIONS OF THEORY AND PRACTICE OF SPACE TELEVISION SYSTEM DESIGN)

P. F. Bratslavets, I. A. Rosselivich and L. I. Khromov

1. TELEVISION RESOURCES FOR SPACE RESEARCH

1.1 Definition, Fields of Use and Classifications of Space Television Systems

The basic principles of a space television system were set forth during creation of the basis of radiotelevision technology. /8* The works of Soviet scientists, A. P. Konstantinov, P. V. Shmakov, P. V. Timofeyev, S. I. Katayev, G. V. Braude and others, facilitated formation of the basis of modern television. For development of space television, the work of the prominent Soviet scientists, S. I. Katayev and P. V. Shmakov, in the field of television played a large part. S. I. Katayev, as early as 1934, introduced the idea of transmission of television images by means of a narrow band of frequencies, which was the basis for small-frame space television systems. P. V. Shmakov proposed a method of retransmission of television broadcast signals, by means of aircraft and artificial earth satellites, which was practically embodied in the creation of the domestic Molniya type satellites. The large association of Soviet scientists and specialists, the work of whom was crowned by successes in the field of space television, acknowledged over all the world, must be given their due. The 4 October 1959 launch in the USSR, exactly two years after the launch of the first artificial earth satellite in the world, of the Luna-3 spacecraft, with small-frame television equipment aboard, for photography of the back side of the moon, was reckoned to be the start of space television. 1960 was the year of the birth of space television. The first direct transmission from space on the USSR and Europe broadcasting networks in the world was accomplished in 1962. Millions of television viewers could observe the transmission of images of the Soviet astronauts A. G. Nikolayev and P. R. Popovich and the working situation around them from aboard a spacecraft.

At the present time, the use of space television has extended its boundaries considerably. With the use of automatic equipment, the program of research on space, the moon, and the planets of the solar system is being successfully performed, and television images of Mars and its satellites have been obtained. /9

The launch of the Luna-16 and Luna-17 spacecraft opened a new stage in lunar research. The Luna-16 spacecraft (and the Luna-20 spacecraft, similar to it), equipped with two panoramic cameras with a 500 mm stereobase, guaranteed the delivery of lunar soil to the earth. The Luna-17 spacecraft delivered the first mobile laboratory, Lunakhod-1, to the surface of the moon; it was equipped with two optical-mechanical, vertical survey television cameras, two optical-mechanical horizontal survey television cameras and two electronic cameras.

*Numbers in the margin indicate pagination in the foreign text.

In the near future, television will permit disclosure of the secrets of such planets as Venus, to the dense atmosphere of which the most powerful telescopes on earth yield.

Meteorological earth satellites (AES) have disclosed new possibilities for meteorological forecasting, and space relays have ha increased the area of television broadcasting by many thousands of kilometers.

Space television is a branch of radioengineering, occupied with the creation of facilities for receiving optical images and transmission of the videoinformation perceived from a spacecraft on other space objects.

Videoinformation can be for scientific purposes or be used for the purposes of servicing AES. Other branches of technology are concerned with receipt and transmission of images: photography and radar, which also are used in mastering space. Television differs from photography, mainly by the method of delivering information to the receiver. Thus, obtaining photographs of the lunar surface became possible after creation of spacecraft which could return to earth. Photography systems cannot generally be used for study of space by means of spacecraft not returnable to earth, or compete with television systems in operational importance of the data. Radar systems receive images of objects, which are irradiated with electromagnetic waves in the radio range. This guarantees all-weather capability of radar observation, in distinction from television, and obtaining images of an object being observed, including information on distance. Observation of space objects, the moon for example, is not bound to meteorological conditions, while the image definition acquires paramount importance. Therefore, the use television in spacecraft also does not compete with radar.

Questions of the advisability of creation of space television systems were discussed before the launch of AES. The large masses, dimensions and energy consumption of television transmitting equipment known at that time constrasted sharply with the proposed resources of AES. /10 Methods of transmission of a wide-band signal over superlong distances were not known.

The basic fieldsof use of television equipment were planned in the initial stage:

- Obtaining high-quality images of space objects (primarily of the Moon, Mars, and Venus), by means of nonreturnable spacecraft;

- Television communications between a spacecraft and earth, for the purpose of observation of the state of the astronaut and the craft;

- Transmission of images of the astronauts and demonstration of their work and surrounding situation directly from space to the television broadcasting network.

The specifics of a space television system are the diversity of problems solved by means of them, increase in data transmission distance, the unique value of the transmitted videodata, requiring high quality of the transmitted image and maximum equipment reliability, the development of nonoperator equipment with minimum dimensions and power consumption, capable of operating under conditions of radiation, solar heat, the cold of space, etc. All this requires special methods of calculation and planning of space television systems. It is advisable to divide the systems by their fields of use and to classify them by various technical characteristics.

Space television systems and equipment can be divided by fields of use into:

- Space videocommunications television systems (space television);

- Television systems for scientific research on space objects;

- Television systems for observation of earth and its cloud cover (meteorological);

- Videotelemetry systems, intended for videomonitoring of the functioning of spacecraft systems;

- Spacecraft control television systems;

- Space television relays.

Simplex and duplex television communication systems are among the space videocommunications television systems (space television); they are used for transfer of television information, both between spacecraft and between a spacecraft and earth, as well as between spacecraft and stations on the planets. The basic purpose of the space television system is transmission of information from person to person.

In distinction from them, television systems for scientific research contemplate collection and transmission of television information from regions of space, by means of carriers, on which it is impossible or inadvisable for man to stay. Such equipment /11 should operate for a long time. At the present time, the tasks of space television equipment for meteorological purposes are being expanded sharply. It is being used for investigation of earth resources, determination of the state of the water surface, snow formation, etc. For AES television apparatus intended for observation of earth and its cloud cover, considerably smaller radiocommunications distances are characteristic than the distances to objects located in deep space (Mars, Venus, etc.). This allows wide-band systems, i.e., it makes possible the transmission of a large amount of data per unit time.

Videotelemetry systems can be closed or open. These systems are installed in spacecraft located at any distance from the ground receiving apparatus. Videomonitoring in space systems has become of paramount importance. Not only ground scientific-technical personnel, but astronauts, use it. Television systems for spacecraft control perform the function of automatic location determination, maneuvering and landing.

Space television relays are used for increasing the distance in space-earth transmission, i.e., for bringing into being space-space-earth television relay chains and for expansion of the communications zone of ground stations, for the purpose of earth-space-earth relay.

Subsequent development of space television has required the application of television broadcasting transmission systems of the type developed for the Soviet Molniya-1 AES, as well as creation of television relays for "official" television, for example, from one AES to another to earth, a planet or a third AES.

The division of space television systems mentioned above, by fields of use, has been enlarged. An especially large quantity of various types of television equipment can be specified for scientific research objects in space. But, while such television systems as videocommunications are easily unified, since one standard scan is used for them, for other areas, in particular, for the area of scientific research television systems, it is difficult to do this.

As an example, we examine the range of light, contrast and dimensional characteristics of one of the space objects which has been studied, the moon. The luminance of the moon during orthogonal illumination of it by the sun reaches 135,000 lux. In proportion to decrease of the angle of the sun above the surface of the moon, this luminance decreases, and it amounts to 0.75 lux during illumination by light reflected from the earth. Such a tremendous range of luminance, naturally, either requires development of different equipment for study of the moon in various luminance regions, or it places /12 special requirements on the planned equipment. The same tremendous range exists in contrast values. The small range of coefficients of reflection (from 0.2 to 0.07) leads to the situation that the contrast of a lunar image during "direct" illumination amounts to 0.01 in all. At small sun angles ("lateral" illumination), because of the absence of an atmosphere on the moon, sharp shadows appear, which increase the contrast practically to unity. The first moon flyarounds were accomplished at distances providing for resolution of details tens and hundreds of meters in size. Upon landing of a spacecraft on the moon, one of the principal tasks was determination of the structure of the lunar surface, for which a resolution of details down to millimeters in size was required of the television equipment. The same broad range of luminance, contrast and the necessary detail exists in carrying out astrophysical research, study of the cloud cover and surface of the earth and of other objects. Even with development of television equipment for installation within a spacecraft, it must be taken into account that the illumination within the craft changes sharply under artificial illumination and upon entry of the direct rays of the sun into the illuminator (from tens to tens of thousands of lux).

It must be noted that the diversity of characteristics of objects transmitted, as well as the radiocommunications conditions, frequently place contradictory requirements on television equipment. Thus, in study of the surface of a planet wide coverage of the surface with high detail, transmission of low-contrast objects with a wide range of contrast, a high rate of accumulation of data with low transmission rate of this information, because of the narrow frequency band of the communciations channel, superhigh sensitivity with a high signal-noise ratio, etc., must be combined. This creates specifications for development of television systems, without taking account of which, it is impossible to develop the optimum version of the equipment.

At the present time, there is no standard classification of television systems in general and of space television systems in particular. In the general course on Television [illegible], the following classification of television systems by their qualitative characteristics was proposed:

- Black-white (monochromatic) television systems,
- Color television systems,
- Three-dimensional (stereoscopic) television systems,
- Color stereo television systems.

The basis for this classification is the most radical qualitative differences of possible versions of data transmission.

For a simpler solution of the problems of creating space television system equipment, it is advisable to classify them into /13 groups with a narrower cross section, each of which has its singularities and, consequently, differences in calculations and planning. According to technical characteristics of the principal devices, space television systems can be divided into the following groups:

1) By type of scanning: mechanical, electronic;

2) By type of storage device: systems with electrical filters, systems with electronic film storage devices, systems with photographic film (photo television);

3) By storage device structure: systems with single-element storage device, systems with line storage, systems with frame storage;

4) By time processes of videoinformation conversion: systems with simultaneous storage and readout processes, systems with separate storage and readout processes;

5) By light conditions: systems with artificial bias lighting, systems without artificial bias lighting;

6) By videosignal spectrum width: wide-band, narrow-band;

7) By type of communications lines: open (with radio links), closed (without radio links).

As an example, the classificiation of modern space television systems by the characteristics mentioned is given in Table 1.1.

Let us briefly characterize these groups of systems.

Systems, in which transmission and receiving image scanning is accomplished by means of mechanical devices, are called mechanical television systems. By virtue of the response of mechanical devices, this scanning is fundamentally low-speed; however, for many television systems, its speed is completely acceptable.

Systems, in which image scanning is accomplished, as a rule, by means of a scanning electron beam (scanning can be accomplished with a light beam and the like), are called electronic television systems.

In systems with an electrical filter, the role of which usually is performed by the video preamplifier, the simplest form of "storage" is accomplished, electrical signal filtration. Such systems, after transformation of light energy into electrical, by means of a photocell, photomultiplier (PM) or dissector, store the energy during a time interval, which is determined by the filter (video amplifier) response. This permits noise of the light-sensitive receiver (photocell, PM, dissector) to be filtered out of the videosignal.

All television systems, using a vidicon, superorthicon and supericonoscope television camera tubes, are systems with electronic film storage. A thin film, installed in a vacuum, serves as the storage device (see section 1.3).

The "charged" image, stored on film, is scanned by an electron beam. The electrical signals formedin this case are amplified, additional synchronization signals are mixed with them and the total television signal is delivered from the output (linear) amplifier, either to the transmitter modulator, to a cable transmission line or directly to a monitor. Electronic systems transmit videoinformation from the information source to the user, with a minimum time loss. /16

Systems which use photographic film as the light image energy storage device belong to the photo television systems. This storage device, in distinction from transmitter tubes, does not require a vacuum, which permits preparation of photographic film with a large area and construction of the corresponding photoelectric equipment. This makes it possible to increase the coverage of the surface being photographed, since readout from photographic film can be accomplished by individual sections, depending on the capabilities of the television readout device. An inherent part of such systems is a high-speed film developer. The developed, fixed and dried film is delivered to the readout device, in which, by means of a mechanical or electronic "traveling beam" device, the light flux passing through the film is converted into electrical signals (see section 4.1).

Systems with single-element storage include systems, in which the light energy of only one element of the image is sensed and stored, and converted into an electrical signal. A dissector, photocell or photomultiplier (PM) is used as the light receiver. In television systems with single-element storage, an electrical filter usually is used as the storage device. Such systems are called systems "without storage" or "instantaneous" systems. However, they can also be storage systems, since storage (filtration) is obligatory for separation of the videosignal from the noise, and the "instantaneous" action of the system is determined by the time constant of the filter (video amplifier) which can reach high values (see section 1.2). In this case, it should be kept in mind that the time constant should correspond to the scanning parameters selected, since, otherwise, because of noncorrespondence of the frequency bands to the pulse duration, the signal-noise ratio deteriorates. By type of scanning, this group is either an electronic system, in the event a dissector is used, or mechanical, if a PM is used as the light-sensitive receiver. A single-element system with PM and electrical filter should have mechanical scanning in two directions (by line and by frame), for standardization of the two-dimensional image. Single-element systems have high-light sensitivity, only in transmission of the images /17
of practically stationary objects. With development of laser technology, more favorable conditions are being created for their development and use. This is all the more desirable, in that high qualitative characteristics can be obtained, in combination with opticomechanical scanning and with small equipment mass and dimensions. Moreover, these systems are advisable for the conduct of photometric research in different sections of the radiation spectrum.

Systems with line storage have a storage device structure, which permits storage of the light energy of only a portion of the image, a line. In engineering practice, these systems frequently are called single-line. Single-line television cameras are analogous to slit cameras. In both cases, to form a two-dimensional image, forward motion of the camera relative to the system being observed is necessary. Transmitting electron-beam tubes, having two-dimensional film storage devices, can also be used in single-line cameras. In such systems, by means of conversion of the image format using fiber optics, the viewing angle of a television system can be enlarged significantly.

/14

TABLE 1.1

Carrier type	System Classification						
	By type of scanning	By type of storage	By storage structure	By storage & readout	By light conditions	By videosignal spectrum width	Launch year
1	2	3	4	5	6	7	8
Luna-3 ISC[1]	Electronic by line; mechanical by frame	Photo television	Frame storage	Separate	Without bias lighting	Narrow-band	1959
Zond-3 ISC	Mechanical	Photo television	Frame storage	Separate	Without bias lighting	Narrow-band	1965
Sputnik-2 spacecraft	Electronic	Vidicon	Frame storage	Simultaneous	With bias lighting	Wide-band	1960
Vostok spacecraft	Electronic	Vidicon	Frame storage	Simultaneous	With bias lighting	Wide-band	1961–1963
Voskhod spacecraft	Electronic	Vidicon	Frame storage	Simultaneous	With bias lighting	Wide-band	1964–1965
Soyuz spacecraft	Electronic	Vidicon	Frame storage	Simultaneous	With bias lighting	Wide-band	1967–1971
Luna-9, Luna-13 LSC[2]	Mechanical	Photomultiplier with filter	Element storage	Simultaneous	Without bias lighting	Narrow-band	1966
Molniya ISC	Electronic	Vidicon	Frame storage	Simultaneous	Without bias lighting	Wide-band	1966
Kosmos-122 and Meteor (daytime system) ISC	Electronic	Vidicon	Frame storage	Separate (Slow-scan)	Without bias lighting	Narrow-band	1966–1972
Kosmos-122 and Meteor (IR system) ICS	Mechanical	With filter	Element storage	Simultaneous	Without bias lighting	Narrow-band	1966–1972

TABLE 1.1 continued

/15

1	2	3	4	5	6	7	8
Ranger ISC	Electronic	Vidicon	Frame storage	Separate (Slow-scan)	Without bias lighting	Narrow-band	1964-1965
Surveyor ISC	Electronic	Vidicon	Frame storage	Separate (Slow-scan)	Without bias lighting	Narrow-band	1966-1968
Lunar Orbiter ISC	Electronic	Photo television	Frame storage	Separate	Without bias lighting	Narrow-band	1966-1967
Mariner ISC	Electronic	Vidicon	Frame storage	Separate (Slow-scan)	Without bias lighting	Narrow-band	1964 1967 1971
Apollo spacecraft	Electronic	Vidicon & secon	Frame storage	Simultaneous	-	Narrow-band	1968-1972
Lunakhod-1	Mechanical	Photomultiplier with filter	Element storage	Simultaneous	Without bias lighting	Narrow-band	1970
Lunakhod-1	Electronic	Vidicon	Frame storage	Separate	Without bias lighting	Narrow-band	1970
Mars-2 and Mars-3 ISC	Mechanical	Photo television	Frame storage	Separate	Without bias lighting	Narrow-band	1971

1[ISC--interplanetary spacecraft.]
2[LSC--lunar spacecraft.]
3[IR--infrared.]

The use of film storage devices in television systems permits storage of the light energy of a two-dimensional image (frame). Simultaneous storage of all sections of a two-dimensional image permits either the highest light sensitivity to be achieved in obtaining television images of rapidly-moving objects or, at the same light sensitivity, reduction in the requirements for stabilization of the onboard television camera, compared with those for single-element or single-line systems. All modern television broadcasting systems, as well as the majority of slow-scan systems, are in this class.

For broadcast television electronic systems (except the telekino system), simultaneous processes of image storage and readout are characteristic. In these systems, the light-sensitive layer of the electron beam transmitting tube is exposed, simultaneously with switching of the tube storage target by the electron readout beam.

In systems with separated storage and readout processes, exposure of the light-sensitive layer is accomplished initially and, then, readout of the stored image from the memory. This mode of operation is inherent in photo television and slow-scan systems.

Television systems with artificial bias lighting contain a special source of radiation. Artificial bias lighting of the object being studied by the radiation source is a means of improving the reflected light conditions of this object. Of course, it is impossible to create bias lighting from great distances with the usual radiation sources. However, the perfection of lasers obviously /18
allows the possibility of engineering accomplishment of such bias lighting.

In space television practice, the terms "narrow-band" or "wide-band" television systems are widely used, depending on the video signal spectrum width. Drawing the boundary between narrow-band and wide-band systems can only be done arbitrarily. Usually, narrow-band systems include systems with a videosignal spectrum width in the range from 0.1 kHz to 0.1 MHz. Systems with a videosignal spectrum width greater than 0.1 MHz are called wide-band. All the modern space television systems enumerated in Table 1.1 are systems which use radiocommunications. However, in spacecraft and manned spacecraft, closed circuit television systems, without transmission into space, are used. Such systems assist a man in controlling the spacecraft in space.

Although today, there still is not a clearly distinguished classification of the technical criteria which characterize space television system apparatus by color or spectrozonal nature, by the use of various stereoscopic methods, as well as by broadening of the frequency spectrum received by television equipment, such apparatus is finding more and more extensive use at the present time in space television systems which have been created.

It is well-known that monochromatic black-white television systems do not transmit all the information on the objects. In this case, a portion of the information, sometimes of unique importance for space research, is lost. By comparing a three-dimensional object and its flat image, deficiencies of the flat image can be found:

- Details located at different distances have different degrees of defocusing and, from this, different resolution;

- A number of parts are lost in a flat record, masked by the nearest details.

Television systems capable of transmitting information as to volume, i.e., various stereoscopic systems, are necessary for full-value image transmission. One of the most promising systems among them is the holographic system.

It must be noted here that, if some information can be disregarded in transmission of accustomed "terrestrial" objects, since our visual memory reproduces the accustomed information, this is not so under space conditions. Color bears a large amount of additional information within itself.

However, any increase in information entails a requirement to increase the throughput capability of a radio television channel, also leads to an increase in mass, dimensions, energy consumption, etc., of the entire AES television system.

Therefore, despite the tremendous importance of transmission of exhaustive information on an object, there must be a compromise between the desired amount of information transmitted and the capabilities of the AES. In particular, one possible version of such a compromise is the use of spectrozonal transmission methods, as well as the use of apparatus with different spectral characteristics. The entire optical range is used in the practical application of space television. /19

Space color television systems (SCTS) can provisionally be divided into three basic groups, by fields of use, principles of construction and methods of signal formation:

- SCTS for transmission of television information on a rapidly-changing situation, i.e., of objects having a high speed with respect to the television observer;

- SCTS for transmission of television information on objects having a low speed with respect to the television observer;

- Photo television type SCTS.

Data on some of these systems are presented in Chap. 5.

As is evident from the classification introduced above, a division of apparatus into regular and slow-scan systems has found no place in it.

As early as the 1930's, S. I. Katayev, in his work, proposed decreasing the frequency band, by means of increasing the frame period to 3-5 sec. This was reckoned to be the origin of the slow-scan or narrow-band area in television.

We are attempting to determine a characteristic, by which one system or another can be considered to be regular or slow-scan Absolute values of the frame frequencies or spectrum width of frequencies transmitted, clearly cannot be an indication of difference in the systems, since, for example, for observation of some industrial processes using stroboscopic effects, frame frequencies measured in hundreds of hertz and regular multi-frame systems for these purposes cannot be defined as multiframe. It is evident that it is most nearly correct to take the rate of change in the information transmitted as a basis, and, with respect to it, to evaluate the properties of the television system, its "time" resolution. In this case, the following definition can be proposed.

If several neighboring frames contain a considerable percentage of identical, repetitive information, determining the basic semantic content of the frame, this is a regular system and, if it does not contain this, a slow-scan one. Slow-scan systems, in which new information is transmitted in each frame, are the most interesting, typical and useful. One of the characteristic indications of being regular or slow-scan systems is the simultaneity or separateness of the storage and readout processes (see Chap. 3).

1.2 Standard Structural Diagram of Space Television Systems and Possible Varieties of Them /20

Before proceeding to description of the structural diagram of the set of devices of the television system, we must dwell briefly on the general structural scheme of the scientific part of radio-engineering equipment of the majority of spacecraft containing television equipment.

All elements of the scientific portion of the radioengineering equipment of the AES can provisionally be divided into five groups (Fig. 1.1).

The first group includes the onboard portion of the radio television system itself. Regardless of the purpose and composition, the task of space television equipment, like any other television system, comes down to transformation of light energy into electricity, amplification of the signals received, mixing synchronization signals and other auxiliary signals with them and transmission of the complete television signal to either a radio transmitter, a memory device or a local videomonitor.

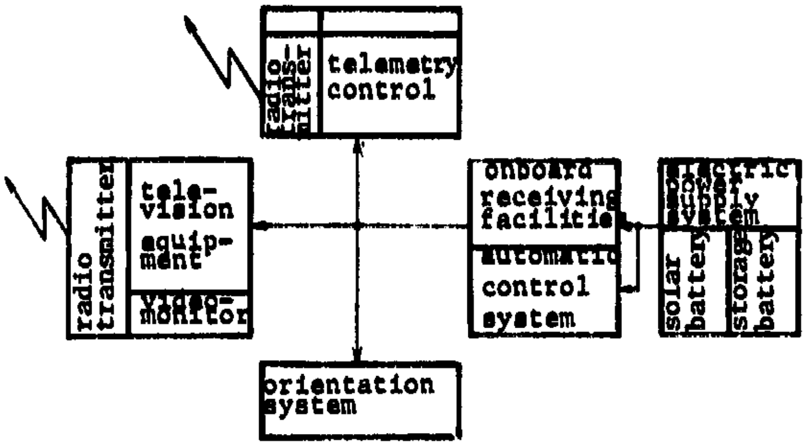


Fig. 1.1. Structural diagram of AES radio-engineering equipment.

The second group of elements provides for orientation of the carrier in space and time. Orientation sensors determine the position of the local vertical and the direction of the movement of the carrier. The stabilization system provides for spatial orientation of the television light signal converter.

The orientation and stabilization systems can be roughly divided into two parts: The first of them determines the position of the satellite with respect to some reference point, for example, the earth, stars or sun. The second part of these systems directly controls the /21 position of the satellite in space. Special clocks make it possible to determine the time of receipt of information, for the purpose of tying this information in to the geographic coordinates.

At the present time, television equipment is being used more and more in orientation and stabilization systems.

The third group of elements makes up the telemetry control, the task of which is control of the most important parameters of the onboard operating equipment and transmission of telemetry data to earth or to the astronaut. For transmission of telemetry data from a long interval of time to earth, there is a memory device in the onboard telemetry equipment. Transmission of telemetry data to earth takes place by a separate, special radio link, although transmission of it sometimes takes place together with television information.

The fourth group includes receiving equipment and facilities for decoding signals received from ground stations and their conversion into the commands, necessary for control of the onboard equipment. Onboard equipment, which automatically generates control signals for onboard equipment from time signals or other primary signals must be included here. The composition of such equipment can include an onboard computer.

The primary power supply system must be the fifth group of on-board elements; it consists of solar and storage batteries and power supply voltage regulation and stabilization systems.

A space television system is a complex set of devices (Fig. 1.2). Transformation of an object of space research to the form of a television picture on earth requires the use of a combination of diverse processes: optical image formation, conversion of the optical image to a videosignal, transmission and reception of the video signal by radio, conversion of the videosignal to an image on the picture tube screen and, finally, making a photo of the picture tube screen and interpreting the photos. Such processes as optical image formation, photography and interpretation are objects of study of large, independent fields of technology: optics and photography. In a television system, these processes are subordinated to the overall requirement of the best representation of the object by a videosignal and its efficient transmission.

The initial optical image of a scene being studied can be reproduced with definite precision from a videosignal transmitted from aboard a spacecraft to earth. Although the technical methods of formation of a videosignal in observation of a natural scene can be diverse, they are based on the processes of conversion of a light flux into electricity, storage of the information and scanning. / 22

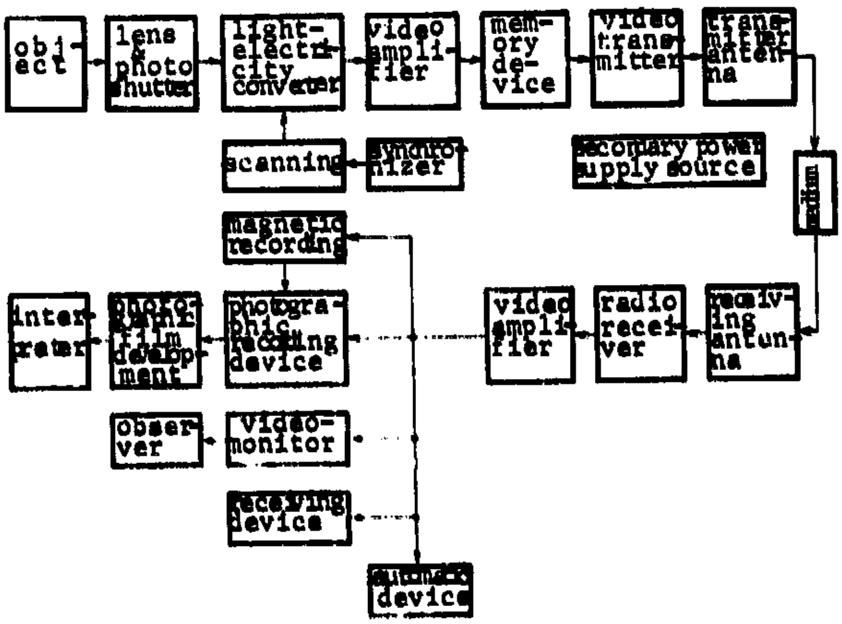


Fig. 1.2. Structural diagram of space television system.

A general standard structural diagram of a television system is presented in Fig. 1.2. The ground portion of this system is examined in greater detail in Chap. 5. We note here only that a characteristic feature of the ground portion of such a television system in the presence of an automatic device, which is a complete ground layout, operating automatically from the incoming television signal.

Composition of the onboard portion of a space television system can have several structural ersions, depending on the field of use and purpose of the particular system. The following versions are the most widely used at the present time: electronic, electronic-magnetic, photo television.

The first version is based on electronic instruments, principally television camera tubes, and it has all the component parts of the structural diagram indicated in Fig. 1.2, with the exception of the memory device. Both tubes in which the function of conversion of the light energy is combined with the memory and the simplest television tube, of the dissector type, can be used as camera tubes here.

Several improved versions of television camera tubes with /23 memories have been developed up to now: isocon, secon, kremnicon, vidicon with secondary electron multiplier and others.

The second version is a combination of an electronic optical-electric converter with a memory device. Despite a series of works carried out on memory devices (the Selectavision system with recording of a hologram by a laser beam, xerographic systems and others), at the present time, the use mainly of magnetic recording devices for the memory, among which the greatest preference is given to cassette type devices, is continuing. A description of the principle of operation of such devices is given in section 4.3.

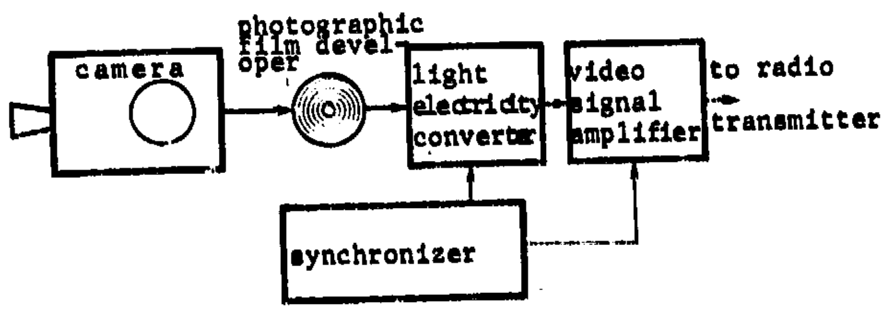


Fig. 1.3. Structural diagram of photo television equipment.

The third version also is a combination of memory and conversion devices, but operating in the sequence indicated in Fig. 1.3, initially, by means of a camera on photographic film, memorization of the information and, then, the light-electricity conversion are carried out.

The specifics of planning a space television system flow from the features of the field of use itself. A television system, as has already been said above, is a set of diverse radioelectronic, optical and photographic devices, to the features of planning for which a number of works have been devoted [13,17,29,30]. The overall creation of a television set, of course, cannot and must not mechanically sum up all the problems of development of various devices serving as links in this system. A television set planner either uses already created links (optics, cathode ray tubes, antennas and others) or only formulates the requirements for development of these links, based on the general purpose of the television system.

Planning a space television system consists of synthesis of the optimum version of a television system, intended for solution of a given, specific problem (obtaining images of a planet, monitoring / 24 the activity of a spacecraft and other things). The optimum system in this case encompasses a whole set of qualitative characteristics: resolving power and viewing angle of the system, energy consumption and mass of the equipment, reliability, cost and other things.

In the process of planning a multilink television system, the planner leans on knowledge of various versions of its links: lenses, cathode ray tubes, radio channels and other things. All of these links have their limitations in solution of the planning task. The entire system cannot be designed, based on the limitations of some one link, for example, radio channels. Only taking account of the properties of all the links in their interconnections with the qualitative characteristics can guarantee solution of the problem of synthesis of the optimum version of a television system.

The problem of synthesis of optimum systems is not specific to space television alone, but to other branches of scientific and applied television. However, in space television, this problem becomes particularly acute, in connection with the high cost of a scientific experiment in space research and, consequently, the high cost of each bit of video data.

The problem of selection of optimum system parameters (frequency bands, number of lines, frame frequency, degree of reliability, energy consumption, stability, mass, cost and other things), applicable to a given purpose of the system, is new for television technology. There is no such problem in planning television broadcasting systems. In fact, it is well-known that the basic parameters of a television broadcasting system (black-white television) are strictly regulated by state standard GOST 7845-55 [31]. In accordance with GOST 7845-55, the frame frequency equals 25 Hz, at a field frequency of 50 Hz, and the number of lines per frame is 625. The

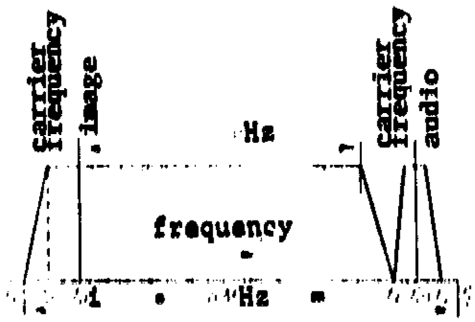


Fig. 1.4. Amplitude-frequency characteristic of radio transmitter standardized by GOST 7845-55.

frequency characteristics of the image signal and audio signal radio transmitters must correspond to those specified in Fig. 1.4 and in Table 1.2. The requirements as to these parameters of the system, which were not encompassed by GOST 7845-55, are established in the technical specifications for television transmission and receiving equipment. Among these parameters are, for example, the frequency characteristics of the video channel of the transmitting equipment in television centers. The technical specifications for this equipment require that the frequency characteristics of the videochannel have a drop of not over 5% in the frequency range up to 7.5 MHz. In broadcast television, the frequency characteristics of transmitting equipment videochannel do not limit the video frequency transmission band. Modern transmitting tubes also are capable of generating videosignals which contain frequencies going beyond the framework of the transmission band standardized in broadcast television. However, in a television broadcasting (black-white) system, the video frequency transmission band is limited by the spread of the image and audio carrier frequencies and, in accordance with GOST 7845-55, $f_{tr} = f_3 - f_{oi} = 6.375$ MHz. / 25

TABLE 1.2

Frequency MHz	Attenuation of power radiated by said transmitter, not less than Image dB	Audio dB	Note
f_1 & below	20	—	$f_1 = f_d - 1.25$
f_2	—	—	$f_2 = f_d - 0.75$
f_3 & below	—	20	$f_3 = f_d + 6.375$
f_4	—	—	$f_4 = f_d + 6.625$
f_5 & above	20	20	$f_5 = f_d + 6.75$
f_{03}	—	—	$f_{03} = f_d + 6.5$

Improvement of the resolution of television images and increase in the amount of transmittable videoinformation in a broadcast television system is possible theoretically, only within the video frequency range up to 6.375 MHz and 625-line discretization of a frame.

Everything which has been stated about the characteristics of planning monochromatic space television systems concerns planning of a space color television system.

The main task in planning color television receivers in a ground broadcast system is achievement of the minimum cost, the closest to the cost of a black-white television set. This problem is not posed in designing a SCTS; on the contrary, the problem is laid down of transferring every complication necessary for operation of the SCTS from the transmitting end of the system, located aboard an AES, to the ground receiving equipment. The specifics of space systems give a great advantage in designing color systems. As has already been pointed out, in planning and calculating monochromatic broadcast systems, the choice of optimum system parameters is impossible, because of limitations opposed by the corresponding GOST. The same thing occurs in planning color broadcast television systems.

For planning a SCTS, the absence of these restrictions is more important than for monochromatic ones. A SCTS in which the basic requirement on broadcast systems, compatibility with monochromatic systems, becomes superfluous, can differ from one another, not only in use of different scanning standards, but by method of transmission of color signals. Both sequential and simultaneous transmission methods can be used in them. /26

The parameters established in GOST 7845-55 are used in the newest modern space television system (radio transmission distance is about 2000 km); it is the space branch of the broadcast television system. The rules of compatibility of equipment for transmission of color and monochromatic images must be strictly observed here, to eliminate the use of two similar types of onboard equipment. A similar system is suitable for observation of the cloud cover of earth, from distances up to 20-40 thousand km. In the future, in proportion to increase in mass of spacecraft and perfection of radio engineering equipment, multiframe electronic systems will be able to handle all orbits more distant from earth. However, it is evident that, in the future, it will be possible to obtain television images of the planets of the solar system, Mars (minimum distance 55 million km), Venus (minimum distance 40 million km) and others, only in a frequency band narrower than 6.375 MHz. Moreover, study of the surfaces of the planets and other space research involve the necessity for increasing the resolving power of the television system to values which greatly exceed those attainable in broadcast television.

Transmission of an image from a distance greater than 0.5 million km and increasing resolution of of television systems to the maximum value, which is determined by the capabilities of the light-electricity converter, as well as a number of other requirements, can be put into practice by means of slow-scan television. Solution of the problem of compressing the frequency band in television transmission of images of rapidly moving space objects and increasing the resolution of television systems is set forth in Chaps. 2 and 3.

In the design and engineering development of onboard equipment for space television, scientific research, meteorology, etc., the primary requirements are: high reliability, dimensions, long service life, compactness, automated operation and the possibility of improving separate elements.

Two more additional requirements are placed on equipment operating directly in space: capacity for operating in the vacuum of space and heat conductivity.

Such concepts as reliability, mass, hermetic sealing and automatic operation are specific for any onboard radio engineering equipment, and do not need explanation.

The service life, i.e., the time of active operation of television equipment, differs in different systems. In all systems intended for scientific research, the service life is short (a few days). In proportion to extension of this research, the service life of television equipment will increase. Up to now, the service life of space video communication systems also has been short. However, in distinction from scientific systems, in space television, it depends, not on the time of conduct of an experiment, but on the stay time of people in the spacecraft. Television equipment for meteorological purposes should have a quite considerable service life. It is desirable that this equipment be able to operate at least one year, 5-6 hours daily; in this case, the equipment reliability during the time of operation should remain high. /27

Compactness of equipment, or the spacefilling factor, is estimated by the ratio of the volume occupied by parts, units and mountings to the total volume of the equipment: $\nu = V_{parts}/V_{equipment}$.

With the change to micromodule and film construction, the spacefilling factor increases sharply. For onboard devices, it must reach values $\nu > 0.75$-0.8.

The possibility of improvement in separate elements is implied by modular design, which permits replacement of any of the modules by more nearly perfect ones.

Under the influence of high vacuum in space, mutual diffusion of metals takes place and normal lubricants disperse. Therefore, it is necessary to avoid rubbing contacts as much as possible, to provide for special lubricants and, in individual cases, hermetically sealed housings. The question of heat regulation is still more complicated than capacity for operating under space vacuum conditions. For artificial internal heat regulation, the stay time of the spacecraft on the illuminated side of the earth and in its shadow must be precisely taken into account. To obtain average temperatures, the most highly heat insulating materials must be chosen.

The maximum microminiaturization, maximum compactness, minimum weight, prolonged operating time with high reliability, operation in vacuum and other requirements lead to bulky specifics, not only for the system, but for the design-engineering development of onboard equipment.

In development and construction of television systems, it must be considered that the requirements of minimum energy consumption, weight and size are placed only on the transmitting (onboard) television equipment. The ground receiving television equipment can be of quite complex design. In distinction from broadcast television systems, the multimillion stock of television sets of which do not permit use in them of complicated technical methods of increasing image quality, in the receiving equipment of a space television system, the use of engineering solutions of any complexity is possible. Decreasing the loss of the most valuable scientific video information /28 in receiving it from space justifies the complexity of the receiving equipment.

Planning of a complicated space television system cannot be completely formalized at the present time. The difficulty is due, on the one hand, to the complexity of the structure of the television system, including a large number of varied links: mechanical, optical, photographic and the radio engineering equipment itself and, on the other hand, the necessity for simultaneously taking account of many, varied planning criteria: the energy consumed, the weight and size of the equipment, light sensitivity and image quality, reliability and cost. The development of space television theory should ease the requirements of the engineers in the stage of formalization of the process of planning specific systems. At the present time, television theory can encompass only the major planning criteria: light sensitivity, technical quality of television images, transmission range, and, based on them, it can give a method of calculation of these system parameters. For this, television theory should include the optimum reception theory and information theory. Much work has been devoted to the use of information theory in television. However, in those works, information theory is drawn on for solution of the problem of compression of the video frequency band of broadcast type television systems, by means of elimination of statistically excessive television images. These works have specified looking at information theory and television as a means of finding different methods of statistically coding television images, for the purpose of compression of the video frequency band. The results of these efforts have been dealt with in detail in work [32].

From the moment of its development, space television has been based on the slow-scan method of compression of the video frequency band and, in this sense, statistical coding has been considered only as a method of a small additional compression of the video frequency band, the efficiency of which is determined by the acceptable degree of complication of onboard equipment.

1.3. Video Signal Formation. Light and Spatial Amplitude-Frequency Characteristics.

The principle of storage (accumulation) of energy is a means of controlling noise. It is based on the use of various relationships for summing up the energy of a repeating signal and random noise. The difference in these relationships leads to an excess of the signal over the noise in summing up their energy. This principle can be put into practice in a television camera in the simplest form, by means of an electrical filter, a video amplifier or, in more complicated form, by means of /29
film storage.

The method of noise control by means of filtration, accomplished by a video amplifier, is inherent in narrow-band mechanical television systems. Let us examine the formation of a video signal in an onboard camera of a narrow-band mechanical television system. Such a camera (Fig. 1.5) has an "instantaneous" solid viewing angle of $\Delta\phi$ steradians. The mechanical scanning device swings a mirror and moves the viewing angle in sequence over the field of observation. In accordance with the content of the section of surface observed (for example, a section of the surface of a planet), the light flux gathered by the lens enters a photomultiplier (PM) and causes modulation of the electron flux at the PM output, i.e., formation of a video signal.

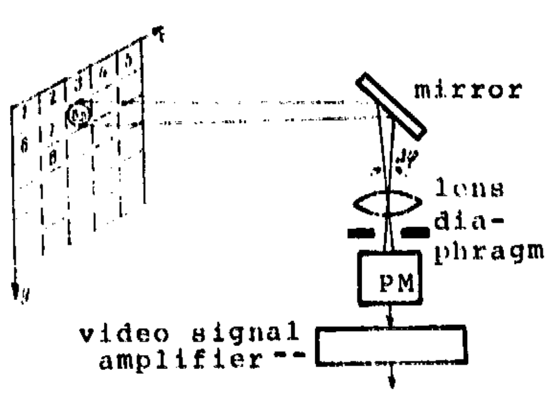


Fig. 1.5. Explanation of operation of television system with single-element storage.

The electron flux, like the photon flux, is a source of noise and, therefore, carries with it the video signal mixed with noise. Extraction of the video signal from this mixture is accomplished by a filter, which is a video amplifier. Owing to the response of the video amplifier, which is evaluated by a certain time constant τ, the energy of this signal and noise is summed up during a finite interval of time equal to τ.

In order to better illustrate the effect of photon noise on the video signal formation process, let us consider the problem of detection of a solitary spot on a uniform background. Let the content of the observed surface section (x,y) be a single white spot on a gray background. We select an instantaneous viewing angle $\Delta\phi$, equal to the angular dimension of the spot. We arbitrarily divide the observed surface (x,y) into elementary sections, each of which subtends solid angle $\Delta\phi$ (Fig. 1.5). The camera filter, in time τ, sums up N_1 photons from elementary section 1 of the surface background (x,y), N_2 from section 2, N_i from the i-th section, etc.[1] The number of photons fluctuates around a mean value in changing from one elementary section of the background to another.

The number of photons summed from each elementary section is a random value, and it is subject to the Poisson distribution law[2]: /30

$$P_m = \frac{\bar{N}_i^m}{m!} e^{-\bar{N}_i},$$

where P_m is the probability of m photons impinging on an elementary section, where m = 0,1,2, ..., $\bar{N}_i$, is the mean number of photons impinging on the i-th elementary section.

As is well-known, for the Poisson dispersion law, σ_n^2, i.e., the noise power, equals the mathematical expectation, i.e.,

$$\sigma_n^2 = \overline{(N_i - \bar{N}_i)^2} = \bar{N}_i,$$

the root mean deviation of the number of photons (photon noise)

$$\sigma_n = \sqrt{\bar{N}_i}.$$

The mean number of photons summed

$$\bar{N}_i = a N^2 T B_{\phi}$$

---

[1] For simplicity, we consider that the quantum yield of the PM equals unity and that there is no inherent noise in the PM.

[2] The statistical approach in determination of maximum sensitivity of television transmitter tubes was first reported in work [8].

where a is the mean number of photons in one lumen per second: $a = 1.3 \cdot 10^{16}$ photon/lm·sec; Δl^2 is the area of the projection of the elementary section of the field observed on the PM (storage zone); B_ϕ is the luminance of the background in the plane of the PM photocathode. When the white spot, with luminance B enters the camera viewing angle, the mean number of photons summed by the storage zone Δl^2 in time T increases to a value

$$\bar{N} = a\Delta l^2 TB.$$

The value of the signal from the white spot on the gray background is determined by the difference in a number of photons:

$$\Delta\bar{N} = \bar{N} - \bar{N}_\phi = a\Delta l^2 (TB - TB_\phi) = a\Delta l^2 T\Delta B, \tag{1.1}$$

where $\Delta B = B - B_\phi$.

It is clear that the signal is directly proportional to the difference in exposure and area of the storage zone. The root mean value of the photon noise of the background

$$\sigma_n = \sqrt{\bar{N}_\phi} = \sqrt{a\Delta l^2 TB_\phi}. \tag{1.2}$$

Dividing quantity (1.1) by (1.2), we obtain the signal-noise ratio of the camera output:

$$q_\Delta = \frac{\Delta\bar{N}}{\sigma_n} = \frac{\Delta\bar{N}}{\sqrt{\bar{N}_\phi}} = \frac{TB - TB_\phi}{\sqrt{TB_\phi}} \Delta l \sqrt{a}. \tag{1.3}$$

It is clear from formula (1.3) that the output signal-noise ratio from a spot with a given area Δl^2 can be improved only by means of increasing the storage time T.

For detection of the spot, it is necessary that the output signal-noise ratio exceed a certain threshold value q_{th}, i.e., condition $q_\Delta \geq q_{th}$, or $\Delta\bar{N} \geq q_{th}\sigma_n$.

The least detectable drop in illumination /31

$$\Delta B_{min} = \frac{\Delta\bar{N}_{min}}{a\Delta l^2 T} = \frac{q_{th}\sigma_n}{a\Delta l^2 T}. \tag{1.4}$$

Substituting the value of the background photon noise (1.2) in (1.4), we obtain

$$[illegible] \qquad (1.5)$$

It is clear from formulas (1.4) and (1.5) that, with given values of B_{av} and $\Delta \ell^2$, the only means of reduction in the threshold value ΔB_{th} of the illumination drop detected (large white square on gray background) is an increase in buildup time T.

By increasing the video amplifier (filter) time constant, with a corresponding slowing down of the scanning rate, buildup times can be achieved, in the type of camera being considered, of 0.04 sec and more. Such an increase in buildup time makes it impossible to obtain images of rapidly changing scenes. If fact, if an image contains 10^6 elements, for a time $T = 0.04$ sec, we obtain a frame transmission time of $10^6\ T = 4 \cdot 10^4 \sim 11$ hours, i.e., the scene being studied must be practically immobile.

The problem of increasing the buildup time during observation of rapidly changing natural scenes has been solved in television, by means of film storage devices in the television camera tubes. A photograph of various types of camera tubes available to television is presented in Fig. 1.6.

Fig. 1.6. Television camera tubes (from left to right): vidicon with 12.5 mm diameter bulb, vidicon with 25 mm diameter bulb, vidicon with 40 mm diameter bulb, secon and superorthicon.

Let us examine the basic processes of video signal formation in cameras with film storage devices. Information on the scene being transmitted is represented, by means of a lens, in the form of a plane optical image, which can describe the spatial function of luminance from coordinate B(x,y). The optical image is formed in a plane /32 light-sensitive layer in the camera tube. Direct interaction between the incident photons and electrons of the material takes place in this layer, i.e., an external or internal photoelectric effect is observed. Therefore, television camera tubes are radiation photon receivers [9, p. 188].

Television camera tubes with external photo effect have a translucent photocathode applied on the inner side of the glass output faceplate. The interaction of the photons with the electrons in the external photoelectric effect is described by the well-known Einstein equation

$$\frac{hc}{\lambda} = eV + \frac{m_e v_e^2}{2}, \tag{1.6}$$

where h is the Planck constant, c is the speed of light, λ is the wavelength of the light, e and m_e are the charge and mass of an electron, eV is the work function of an electron in electron volts, v_e is the velocity of the emitted electron.

The external photoelectric effect is observed for radiation with wavelengths in the optical range, from the ultraviolet to the red limit λ_{lim}. The red limit of the external photoelectric effect is determined from the Einstein equation at $v_e = 0$:

$$\lambda_{lim} = hc/eV. \tag{1.7}$$

In vidicon type television tubes, the internal photoelectric effect in various semiconductor photo layers is used. The red limit wavelength in the internal photoelectric effect can be determined from formula (1.7), where the value of eV should be treated as the forbidden bandwidth in electron volts [9, p. 202].

Besides the external or internal photoelectric effect, processes of storage and readout of the charged image, in combination with amplification of the electron flux, takes place in television tubes.

In tubes of the supericonoscope, superorthicon and secon types, by means of secondary emission or secondary conductivity in the storage (transfer) section, amplification of the electronic image is achieved. Amplification of the electron flux is used in the readout section, by means of a secondary electron multiplier (SEM).

Let us examine the processes of storage and readout of a discharged image taking place in the tubes.

Storage Process

Vidicon. A translucent metallic layer of the signal plate and thin semiconductor film, having internal photoelectric effect, the film storage device, is applied on the inside of the end glass faceplate of the vidicon (Fig. 1.7). During the time of exposure, under the action of the optical image B(x, y), focused in the plane of the film storage device, a latent image forms on the surface of /33 the storage film facing the electron beam, in a form corresponding to the image of the distribution of charges Q(x, y, t), which we call a "charged" image for short. By analogy with the optical image, it can be estimated by the value of the drop ΔQ between parts of the image, as well as by the contrast ΔQ/Q. The process of formation of the charged image is characterized by time response. With increase in exposure time T, the excess of the value of the drop ΔQ between two light halftones above the noise power of the charged image (graininess, caused by the discrete nature of electrical charges) increases [10]. This process is the essence of the storage method in the vidicon and other camera tubes.

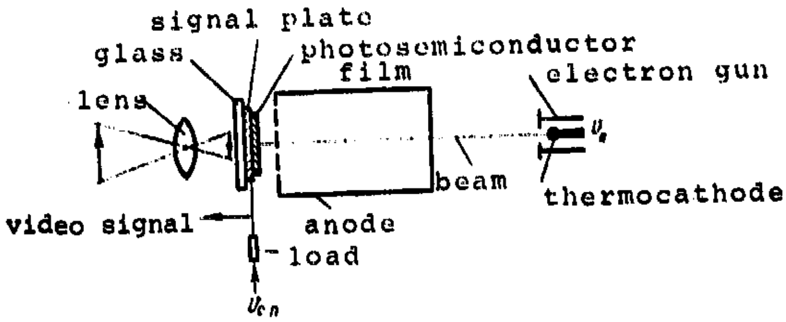


Fig. 1.7 Diagram of vidicon

Supericonoscope. The optical image is focused in the plane of the translucent photocathode of the tube (Fig. 1.8). The stream of photoelectrons is transported to the storage device, a dielectric film, by means of an electromagnetic focusing system, on the other side of which there is /34 a metallic signal plate. Bombardment of the dielectric film by photoelectrons causes secondary emission. The secondary electrons are collected by a cylindrical collector surrounding the storage device. An accelerating field between the collector and storage device (tube target), which can differ, depending on the equilibrium or nonequilibrium recording mode (see section 3.6), determines the fraction of the secondary electrons removed.

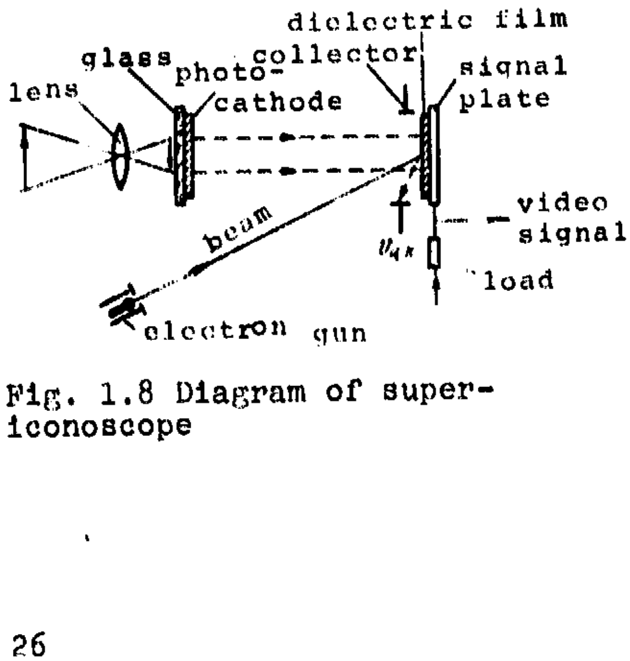


Fig. 1.8 Diagram of super-iconoscope

As a result of bombardment of the film with photoelectrons and secondary emission, a charged image Q(x, y, t) is built up on the surface of the film storage device.

Superorthicon. The buildup process in the superorthicon is similar to the process in the supericonoscope. The difference between the build-up section of the superorthicon (Fig. 1.9) and the build-up section in the supericonoscope is that the secondary electron collector does not have a cylindrical shape, but the shape of a fine-mesh grid, which is located in direct proximity to the surface of the film storage device being bombarded by photoelectrons.

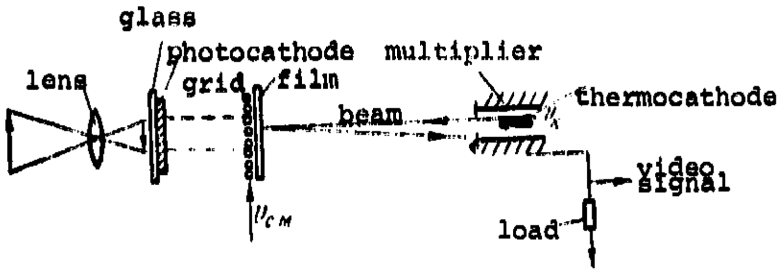


Fig. 1.9 Diagram of superorthicon

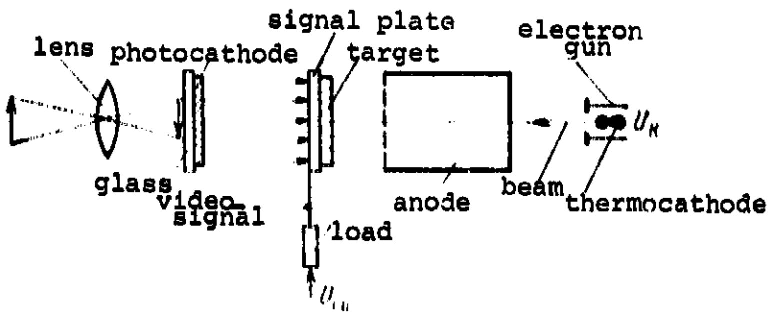


Fig. 1.10 Diagram of Secon

Secon. The storage device in the secon (Fig. 1.10) is a dielectric target, operating by use of secondary electron conductivity. The stream of photoelectrons is accelerated to an energy on the order of 6-10 keV in the transport section, it penetrates a thin metal signal plate and falls on the target. The target material is a porous dielectric [11]. Under the action of high-energy photoelectrons, a large number of free secondary electrons, having a low energy level, is formed in the target dielectric. Under the influence of the electric field of the target, these electrons are directed through the pores of the dielectric to the signal plate, and a charged image corresponding to the optical one forms on the target. For each incident photoelectron, there are 30-100 secondary electrons on the average reaching the signal plate. Consequently, amplification of the electron image with a very high coefficient is accomplished before the buildup process in the secon.

Readout Process

The charged image, formed as a result of the buildup process, can be read out from the film storage device, by scanning it with a sharply focused beam of fast electrons, causing secondary emission with a coefficient $\sigma<1$ ("hard" readout beam) or by a beam of slow electrons with $\sigma<1$ ("soft" readout beam). The processes of readout of video information from the target by a "hard" or "soft" beam have much in common. In both cases, the main bulk of the electrons reflected from the target by the "soft" beam and secondary electrons with the "hard" beam have low initial velocities, on the order of 1-10 keV.

The charged image $Q(x, y)$ on the film storage device, together with the charges on the camera tube electrodes, creates a field, the voltage of which in the vicinity of the film corresponds to the value of the charge. We call the distribution of the potential in the plane of the storage device $U(x, y)$ the "potential" image. The potential drop $\Delta U(x, y)$ in the storage device causes modulation of the flux of low-speed electrons (reflected or secondary electrons) during scanning by the beam, i.e., they are the cause of formation of a video signal. The video signal current value can be estimated by the approximate formula $I_s(t) \approx S(U_0)\Delta U I_b$, where I_b is the readout beam current, ΔU is the potential drop in the film storage device, U_0 is the constant potential difference, determining the constant component of the voltage of the field in the area of the storage device, $S(U_0)$ is the mean slope of the current-voltage curve of the element read out of the film storage device.

For readout of a charged image with a total charge Q_M, the electron beam should introduce a charge $Q_{ro} = I_b T > Q_M$ in the frame length time T.

The interaction of the beam electrons with the $U(x, y)$ field in the plane of the storage device (target) leads to generation of two signal currents. Applied to the vidicon and secon tubes, it /36
is target current I_{c1}, taken off the signal plate, and current I_{c2} of secondary emission electrons, going from the target to the anode or to the SEM: $\sigma I_b = I_{c1} + I_{c2}$.

Each of the currents I_{c1} and I_{c2} is modulated by the $U(x, y)$ field and carries information on the stored image. In the vidicon and secon, current I_{c1} is the video signal, flowing in the signal plate circuit. In the superorthicon and vidicon with SEM, using a slow electron beam for readout, current I_{c2} is the video signal, entering the SEM, where it is amplified 250-1000 times (Fig. 1.11).

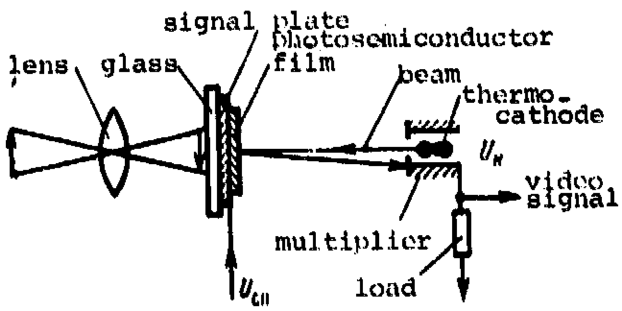


Fig. 1.11 Diagram of vidicon with SEM

In the electron beam scanning process, discretization of the image takes place in the plane of the film storage device and charged image readout, into individual lines (the video signal is continuous within a line) or into individual "points" (the pulse readout method)[12]. Information on the start of each line is transmitted by means of auxiliary pulses, generated by the synchronizer [13].

A television camera tube can be considered to be a video signal current generator, having a very high internal resistance. The value of the video signal current is determined by the scale (amplitude) of a pulse of current I_c, formed in readout of the charged image from a white square of large size on a black background [14]. It is very simple to obtain an approximate estimate of the value of I_c. Readout of the charge is accomplished by a focused electron beam, forming a readout spot on the target with dimensions Δl_x and Δl_y, by line and frame, respectively. The value of the readout spot charge $\Delta Q = e\rho(BT)\Delta l_x \Delta l_y$, where $\rho(BT)$ electrons/mm is the density of the electrons stored in 1 mm^2 during exposure time T of the white square with luminance B, lux.

The charge ΔQ is read out in time $\Delta t = \Delta l_x / v_{ro}$, where v_{ro}, mm/sec is the scanning rate of the readout beam along a line.

In this case, current /37

$$I_c = \eta \frac{\Delta Q}{\Delta t} = \eta e \rho(BT) v_{ro} \Delta l_y \tag{1.8}$$

is formed, where η is the readout efficiency.

The size of the spot read out across a line depends on the size of the target l_Φ and the number of lines scanned z, and it does not exceed a certain value

$$\Delta l_y = d \frac{l_\Phi}{z} \leqslant \Delta l_{max}, \tag{1.9}$$

where d is a coefficient.

Substituting (1.9) in (1.8), we obtain an approximate estimate of the video signal current, as they say, from a large detail

$$I_c = \eta d e \rho(BT) v_{ro} \frac{l_\Phi}{z} \tag{1.10}$$

or

$$I_c = \eta d e \rho(BT) \frac{l_\Phi^2}{T_{ro}},$$

where

$$T_{ro} = \frac{z l_\Phi}{v_{ro}}$$

is the frame readout time.

Formula (1.10) shows that the video signal current, determined by the density of the stored electrons $\rho(BT)$, in the first approximation, is directly proportional to the scanning rate v_{ro} and inversely proportional to the line density z/l_Φ.

Unfortunately, for formula (1.10), it is difficult to calculate the derivative of the coefficients ηd, determined by the ratio of the useful charge read out to that stored on a tube target with area l_Φ^2:

$$\eta d = \frac{I_c T_{ro}}{e\rho(BT) l_\Phi^2}.$$

This situation, in combination with the nonlinear dependence of stored charged density ρ on exposure BT, causes the video signal current I_c to be found, not by calculations, but experimentally.

Let us turn now to questions of formation of a video signal in a phototelevision transmission system (PTS). Photographic film is used as a light-sensitive element here. During the exposure, under the action of the optical image focused in the plane of the photographic emulsion, a latent photographic image is formed. The process of formation of the latent image is characterized by time inertia, i.e., with increase in time, the exposure increases the number of development centers in the photographic emulsion layer.

After development, fixing and drying, the negative is delivered to a photoelectric converter. The chemical process of development increases the effect of light by more than 10^6 times. /38

Readout of the photographic image is accomplished by scanning it with a focused light beam (a traveling beam device or optical-mechanical readout device).

The image on the negative modulates the light flux entering the photomultiplier, which converts it to a video signal.

In scanning the plane of the photographic negative, discretization of the image into individual lines takes place. Both the photographic and television subsystems participate in formation of the video signal. For planning a phototelevision system, reducing the photographic signal and the photographic noise into the video signal is of great importance. The maximum signal scale on photographic film corresponds to the density difference of the negative $D_{max} - D_{min}$; in the working section of the characteristic curve of the photofilm, it is a linear function of exposure (Fig. 1.12). The noise value is determined mainly by the root mean fluctuation of the negative darkening from the mean value of its density. This value changes with change in the mean density of the negative (Fig. 1.13):

$$\sigma_D = \mathrm{const}\sqrt{\frac{a}{\Delta l^2}\bar{D}}$$

where const is a proportionality factor, a is the area of projection of a grain, $\bar{D}$ is the mean density value, Δl^2 is the area of the scanning aperture.

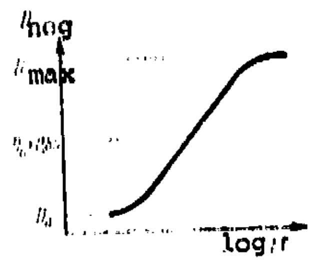


Fig. 1.12 Photographic film characteristic curve

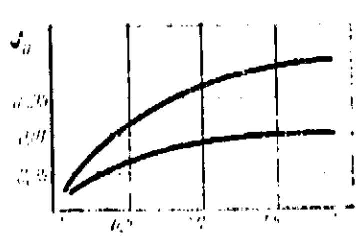


Fig. 1.13 Photographic noise vs. negative density for two types of photographic film

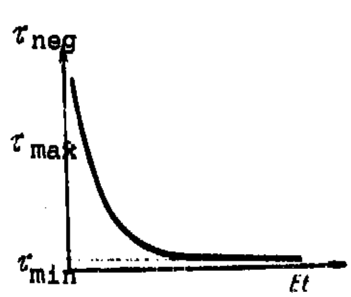


Fig. 1.14 Negative transparency vs. exposure

Usually, in calculations of photographic systems, the value of the noise measured by an aperture 24 µm in size, in sections of the negative with a density of 0.85 above the density of the fog. In the process of read- /39
out of the photographic image, the video signal is proportional to the transparency of the photographic negative τ_{neg}. In this case, its maximum value is standardized from the value $\tau_{neg\ max}$. The minimum value of the video signal corresponds to $\tau_{neg\ min}$. The minimum signal amounts to 0.01-0.02 $\tau_{neg\ max}$ in all. Thus, the video signal in a phototelevision camera is standardized and it is a nonlinear function of exposure (Fig. 1.14).

One of the advantages of the phototelevision system is the possibility of sequential (by section) readout of the image from the photographic film which, with the same equipment unit data, permits an increase in definition by means of increasing the transmission time.

The results of the processes of transformation of the optical image into the electric video signal in the television camera are evaluated, by means of light and spatial amplitude-frequency curves.

The light and spatial amplitude-frequency curves are found experimentally, i.e., by means of testing the camera tube in a laboratory installation. In calculations, these characteristics can be approximated by formulas, taking account of the characteristics with different scanning standards.

In measurement of the light characteristics, a light square (or rectangle), with luminance B, on a black background B_b, is projected on the photo layer of the tube. The dimensions of the white square are made quite large (on the order of 0.1 of the several layer dimensions). The luminance of the black background B_b is held constant; in the first approximation, $B_b = 0$. The dependence of the video signal current pulse amplitude, formed by illumination of the white square on a black background, on the variable illumination of the square is measured:

$$I_c = I_c(B)\Big|_{\substack{B_b=0 \\ T=\mathrm{const}}} \qquad (1.11)$$

Function (1.11) is called the light characteristic. Examples of light characteristics of television tubes are presented in Fig. 1.15. The closeness of the concept of light characteristic in television and the characteristic curve in photography is obvious. This similarity increases, if, not the luminance value B, but the exposure value BT, is plotted on the abscissa of the light curve, taking account of the interchangeability of B and T (see section 3.2), and it is changed to a logarithmic scale.

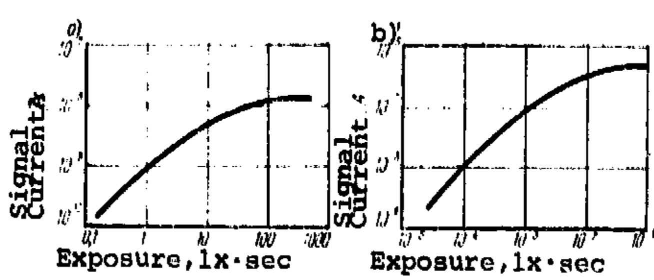


Fig. 1.15 Light curves:
a) slow-scan vidicon (frame readout time 10 sec), b) secon (frame readout time 1/30 sec), from data of work [11]

The saturation section of the light characteristic is explained by the capability of the film storage device (target) of the tube to build up only a finite electrical charge, by /40
virtue of limitations of the capacitance of the storage device and the potential difference. This places an upper limit on the operating range of the exposure. It is limited from below by the threshold value of measurement of the video signal current. The working range of illumination from B_{th} to B_{lim}, reproducible by the television tube, is significantly less than the range of illumination on observed space objects.

By varying the exposure time, light filter density and diaphragm opening, the limited range of illumination of a natural scene of interest to an observer can be matched with the operating exposure range of the television tube. The density of the neutral light filter and relative diaphragm opening of the lens regulate the illumination on the photo layer, in accordance with formula

$B = \frac{1}{4}\tau_1\tau_2 O^2 B_{ob}$ where B_{ob} is the illumination of an object having a coefficient of reflection τ_1; O is the relative diaphragm opening of the lens and τ_2 is the transmission coefficient of the light filter, together with the lens.

Fig. 1.16 Distribution of illumination along a line

However, a correct choice of exposure still does not guarantee reproduction of an object, describable by the the dependence of illumination on the $B(x, y)$ coordinates, called the optical image. This function has very small drops in illumination ΔB, determined by the difference in coefficients of reflection of parts of the object (Fig. 1.16). Let an optical image $B(x, y)$ contain a detail, in the form of a white spot (square), with luminance B, forming an illumination drop ΔB to a gray background B_b. It is evident that, for reproduction of the drop, condition (1.4) must be satisfied; it was established for an ideal summation of photons /41
and with the assumption of an unlimited, rectilinear light characteristic. Nonlinearity of the light characteristic must be taken into account. The video signal current from a white spot on a gray background can be found from the light characteristic, as the difference in currents (Fig. 1.17)[1]: $\Delta I_c = I_c(BT) - I_c(B_bT)$.

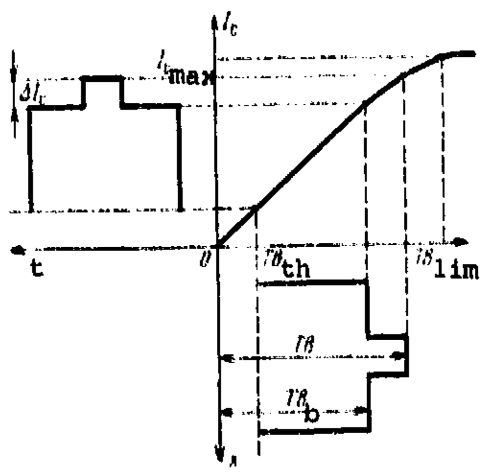


Fig. 1.17 Finding video signal from light curve

In connection with the fact that the light curve of a camera tube has a saturation section, the task of effective use of the relatively narrow operating range of illumination arises. The difficulty arising here is caused mainly by the fact that, as is well-known, the luminance of an incoherent optical image cannot be subtracted. However, conversion of the luminance of an optical image into charges, potentials and currents makes it possible to subtract values and to carry out other, subsequent special processing

[1]The superorthicon reproduces a small bright detail when operating in the saturation section of the light characteristic, owing to the operation of subtracting the background potential in the target of the tube, determined by redistribution of the secondary electrons.

operations. It is evident from Fig. 1.16 that function $B(x, y)$ does not fill the range of illumination from B_{th} to B_{lim} uniformly, which is explained by the presence of envelopes of the "white" B_w and "black" B_b functions, which are plotted by dash lines in the graph. Elimination of these envelopes would permit development of the charged image on the target, with the purpose of more efficiently using the dynamic range. Such developing, as applied to the video signal current, is reported in greater detail in section 3.8. It is based on elimination of the image envelopes, with subsequent carrying out of the subtraction and division operations. A difficulty arises in camera tubes with elimination of the spatial potential distribution envelopes on the target. The cost of reduction of efficiency in the developing can change to a more easily accomplished method, subtraction of the mean background component on the target, by means of irradiation of the target with a compensating electron flux (see, for example [15] page 160).

The concept of contrast k is widely used in television; it is /42 defined as a relative value of the illumination drop with varied standardization:

$$k_1 = \frac{B - B_b}{B} = \frac{\Delta B}{B_b + \Delta B}, \quad k_1 \in [0, 1],$$
$$k_2 = \frac{B - B_b}{B_b} = \frac{\Delta B}{B_b}, \quad k_2 \in [0, \infty],$$
$$k_3 = \frac{B - B_b}{B + B_b}, \quad k_3 \in [0, 1]. \tag{1.12}$$

Conversion of light contrast, determined by formula (1.12), into the electrical contrast of the video signal is accomplished, taking account of the contrast coefficient of the light characteristic, expressed in the logarithmic scale:

$$\frac{\Delta I_c}{I_c} = \gamma \frac{\Delta B}{B_b}, \tag{1.13}$$

where $\gamma = \frac{\Delta \log I_c}{\Delta \log B_b T}$ is the contrast coefficient of the light characteristic $\log I_c = \phi(\log B_b T)$ on the logarithmic scale.

It is clear that the contrast coefficient of the light characteristic is a function of exposure $\gamma = \gamma(B_b T)$.

The electrical contrast $\Delta I_c/I_c$ of the video signal can be changed, by means of operation above the potential contour on the camera tube target or above the video signal. The electrical potential on the tube target and the electrical video signal permit, in distinction from illumination, the operation of subtraction, which can increase contrast to the maximum value. This operation is called the video signal contrasting operation. It is used in video amplifiers.

In the dependence of the video signal current ΔI_c on the two light quantities ΔB, B_b (see formulas [1.12]) can change to the arguments k, B_b, which include the concept of contrast.

The process of light-electrical conversion is evaluated from the light characteristic for large details of an image. The light-electrical conversion for small details is evaluated, by means of the spatial amplitude-frequency characteristic, determination of which involves a linear model of a television system.

1.4 Conditions of Feasibility of System. Selection of Basic Television Parameters.

For calculation of any television system, the initial data, the planning criteria, are needed. The latter are determined as functions of the field of use, purpose and characteristics of the /43 object being studied (subject) and the means of observation. All planning criteria values are reduced to a technical task (TT).

Planning criteria must be divided into two groups: primary and supplementary.

Among the primary planning criteria, in accordance with the information problems of television, are requirements as to image quality, light sensitivity and transmission distance.

Based on these requirements, the primary television parameters of the planned television system are determined (calculated): number of lines, frame length, amplitude-frequency characteristic of television system, video frequency band, sensitivity of light electricity converter, transmitter power and antenna gain.

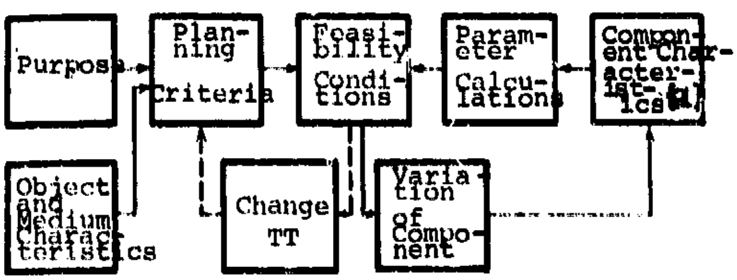


Fig. 1.18 Diagram of conduct of calculations in planning.

The conditions of feasibility of a planned television system consists of the possibility of selection of those primary television parameters, at which the television system created completely satisfies the requirements of the primary planning criteria (TT requirements). Calculation to determine feasibility of a television system is presented by the diagram in Fig. 1.18. The calculation of the system parameters is carried out from the characteristics of existing components, for the purpose of achieving the assigned values of the planning criteria. All possible combinations of the component characteristics are analyzed. If the results obtained with any combinations of the characteristics of existing components give a negative feasibility condition, a second calculation, fixed by the characteristics, must be carried out, of components which are absent, but which can be created. In this case, if one does not succeed in satisfying the conditions for feasibility of the system, the values of the technical task parameters must be reexamined.

General specifications for preliminary selection of the primary television parameters are given below. The theoretical bases and methods of calculating them are given in Chaps. 2 and 3.

The criterion of quality of the image received is the most /44
complicated and varied of the primary planning criteria assigned. In the process of planning a space television system, the engineer must so select its components and match them, that acceptable television image quality is insured, with the assigned design and operating requirements for the equipment. For this, the planner must have a method of calculation of the qualitative image characteristics (optical, photographic and television), including allowance for the effect of the television system parameters: number of lines, frame frequency, frequency band and other things. Unfortunately, the problem of calculation of image quality has not been completely solved up to now. The difficulty in solution of this problem is explained by the fact that an estimate of the quality of television images is one of the types of complicated solutions perceived by the brain (higher branches of the visual analyzer) of the observer, on the basis of unknown criteria. The difficulty is aggravated by the fact that these criteria, strictly speaking, must consider the emotional and semantic properties of the image.

However, they may be disregarded, if one is limited to narrowly professional tasks of planning television systems. In fact, in the function of the engineer-planner, only the choice of the values of parameters of the proposed equipment are included, which affect the "technical" quality of the image, and not the semantic or emotional content of the transmitted image. An engineer planning a television system is obliged to provide the required "technical," nonsemantic image quality. The competence of introducing such a concept is confirmed by experience in designing optical, photographic and television systems. In the technologies of television, photography and optics, the terms "image quality" and "image quality criteria" have long been used, only in the nonsemantic aspect of these concepts.

The concept of "technical quality" of an image can be explained by the following example. Let an observer compare images of a certain natural scene, formed by two different systems, system No. 1 and system No. 2. One's life experience is evidence that, regardless of the emotional and semantic aspects of an image, an observer is capable of giving one of three answers:

-- The first system provides higher image quality;

-- The second system provides higher image quality;

-- The systems provide identical image quality.

In particular, if system No. 1 is a motion picture and system No. 2 is a television broadcast, it is well-known from everyday experience that all viewers evaluate image quality in the motion picture as better. Viewers draw this conclusion, regardless of the artistic and semantic virtues of motion pictures. This fact /45 confirms that, both in a motion picture and in television, a viewer is capable of extracting a narrower group of qualitative indicators from the many aspects of quality, depending, not on the emotional and artistic virtues of the images observed, but on various types of distortions introduced by the motion picture or television equipment. This narrow group of quality indicators composes technical image quality.

Introduction of the concept of technical quality of television images in no way means refusing to take account of the properties of the information receiver, the visual analyzer. The matter concerns only rejection of consideration of the emotional and semantic aspects when a man perceives television images. However, with this rejection, the role of the information receiver remains large. Therefore, one of the important questions for television technology is the question of establishment of accuracy criteria (the terms "fidelity criteria" or "quality criteria" sometimes are used) of reproduction of television images. On the one hand, such criteria should reflect the properties of the receiver of television information, the visual analyzer and, on the other hand, have a mathematical expression for calculation of systems being planned. The most widespread accuracy criteria in communications theory is the root mean deviation. Its signal $m(t)$ is reproduced by distorted signal $y(t)$, the root mean deviation $\varepsilon^2 = M[m(t) - y(t)]^2$ where M is the sign of the averaging operation (mathematical expectation).

There are two diametrically opposed opinions as to the applicability of the root mean deviation ε^2 as a criterion of accuracy of reproduction of television information. According to one opinion [32], this criterion is unsuitable for television information. This opinion makes it impossible to extend the achievements of existing theory of optimum reception and transmission of information to television technology. According to the other opinion [33], the root mean deviation is suitable for television information and, consequently, the results of the theory of optimum reception of information can be used for engineering calculations of planned space television systems [33, 34].

The purpose of the television system is to detect and interpret, with probability P_{int}, a television image of an object M in coverage of an area L, luminance B_M, contrast k and transmission distance R. It follows from this general formulation of the purpose of the system that the quantities P_{int}, L, B_M, k and R are the planning criteria.

A television system can be intended for both detection of objects of simple shape, for example, points, and for detection of objects of complex shapes. In the first case, the problem of detection and measurement of the coordinates of a signal of previously known shape is solved. This problem concerns one of the branches of the statistical theory of decisions [3]. /46

The area coverage depends on the viewing angle of the system and the distance to the object being observed H. In the simplest case, disregarding curvature of the earth, $L = 2H \tan \alpha$.

The viewing angle of the system (Fig. 1.19) is determined by the focal length ℓ_{foc} of the lens and the frame size ℓ_f in the light-sensitive layer:

$$\tan \alpha = \ell_f / 2\ell_{foc}, \qquad (1.14)$$

i.e., $L = H\ell_f/L_{foc}$, where H is the altitude of the AES flight trajectory.

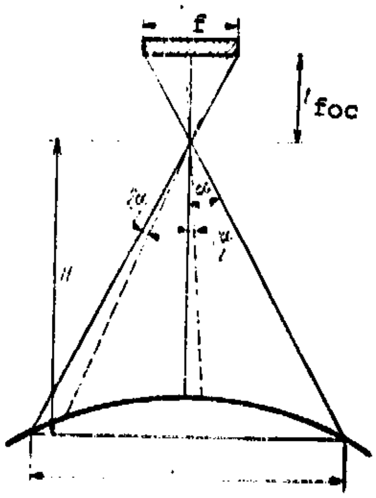


Fig. 1.19 Explanation of decrease in resolution at the edges of an image.

With a given signal-noise ratio, the probability of identification (interpretation) of observed objects is determined by image definition.

Definition of a television frame is determined from the formula $N = z\,2D\ell_f$, where z is the number of lines per frame, D is the resolving power along a line and ℓ_f is the line length on the photo layer of the tube.

With a square raster and identical line and frame resolution, definition $N = z^2$ elements.

The resolution of the object of observation D_f depends on many factors, including the scanning standard adopted, flight speed of the spacecraft and its distance from the object of observation, exposure time, characteristics of the object and of the television tube, the video amplifier and communications channel frequency bands, as well as similar data for the receiving equipment. Based on given values of the linear dimensions of a detail discriminated σ, minimum number of lines (elements) in the detail of the image Δz, the linear dimensions of the working surface of the camera tube target ℓ_f, focal length of the lens ℓ_{foc} and distance from the lens to the object being studied H, the necessary number of lines can be found by the formula

$$z = \frac{\Delta z \ell_f H}{\sigma \ell_{foc}}.$$

Taking account of the curvature of the earth, the size of an element being resolved σ_f will change, depending on the distance of the element from the center of the field of view (Fig. 1.19):

$$\sigma_f = H \sec^2 \alpha \frac{\sin \frac{2\alpha}{N}}{\cos \frac{2\alpha}{N} - \tan \alpha \sin \frac{2\alpha}{Z}}.$$

As is evident from the formula, the resolution decreases in proportion to the square of the sec of half the viewing angle, i.e., it drops sharply at the edges of the image.

A peculiarity of a spacecraft is its constant motion with respect to the object observed (with the exception, of course, /47 of the intraspacecraft space television system). This movement is complex, since, besides orbital motion, a satellite has inherent oscillatory or rotational motion. As a result of this motion, during the exposure time of a television frame, movement of it takes place, affecting image definition.

It is customary that movement of a frame during the exposure time by an amount $\Delta \leq 1$ is considered to be acceptable in practice. The actual movement can be found in a simplified way from the following formulas:

In linear motion $\Delta = \frac{v T_e}{L} z$

elements, where v is the AES flight speed, T_e is the target illumination time (exposure), L is the linear size of the observation zone and z is the number of lines or scanning elements:

In rotational motion $\Delta_\omega = \frac{\omega T_e}{2\alpha} \geq 1{-}2$ elements, where ω is the angular velocity and 2α is the viewing angle.

The connection of definition or resolution to image interpretation is well-known in photography.[1]

The monotonic relation between interpretability of television images and resolution of television systems is illustrated by the graph represented in Fig. 1.20. The interpretation probability is plotted on the ordinate and, on the abscissa, the resolution, a quantity which is the reciprocal of the resolution threshold of the two lines.

Sensitivity of a space television system is determined by the minimum illumination, at which the system gives an image of the object with the assigned definition.

A peculiarity of space television systems is the necessity of transmission of remote objects, having reduced contrast, in distinction from studio broadcast television transmissions, where the contrasts of the objects transmitted reach values on the order of 0.6-1.0. Therefore, in the majority of cases, the sensitivity of /48
a space television system must be determined at low contrast.

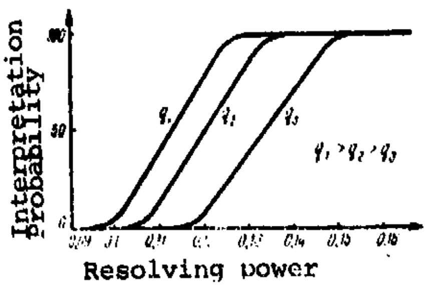


Fig. 1.20 Probability of interpretation of a television picture vs. resolving power of the system and signal-noise ratio q

Illumination in the plane of the photolayer, as a function of illumination of the object (terrain) B_M is expressed by the formula

$$B = \frac{\beta T_0 B_M \breve{O}^2}{4},$$

where $\breve{O}$ is the lens speed or aperture ratio, β is the coefficient of reflection of the object and T_0 is the transparency of the medium and lens.

---

[1]This conclusion, based on aerial photography experience, clearly concerns resolution, measured by means of a globe containing two lines, which is distributed in England [35].

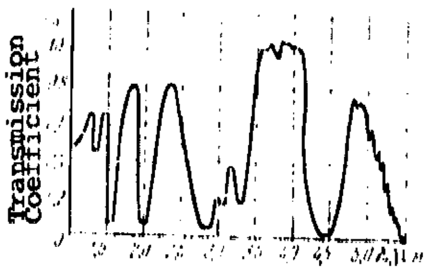


Fig. 1.21 Transmission coefficient of atmosphere vs. wavelength in the presence of moisture

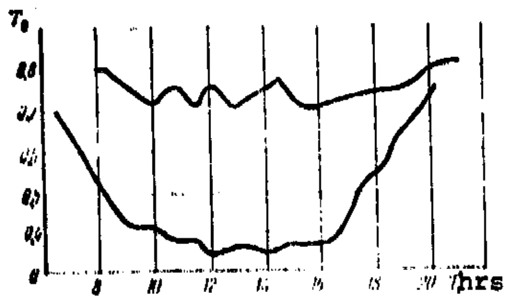


Fig. 1.22 Example of change in transmission coefficient of atmosphere for $\lambda = 0.55$ µm in the course of a day

As is evident from the formula, illumination in the plane of the photolayer does not depend on the distance to the object. Besides illumination of the object and the characteristics of the optical element, illumination of the photolayer is directly proportional to the transparency of the medium. Therefore, it is necessary to take account of the variability of the medium in calculations. Thus, for example, the transmission coefficient of the atmosphere vs. wavelength in the presence of moisture and for different times of day are shown in Figs. 1.21 and 1.22, from which it is clear that the transmission coefficient of the atmosphere vs. wavelength and observation time change strongly. In planning television systems for meteorological purposes, the sensitivity of the system determines the length of operation in the course of a day. The amount of light energy reflected by the cloud cover, earth and expanses of water depend on the latitude and longitude of the location, the date and hour of the day, and condition of the atmosphere and the surface of the earth. /49

Isoluxes of illumination of the earth at 30,000 lx, as a function of time of year, day and terrestrial latitude, actually vs. sun height, is presented in Fig. 1.23.

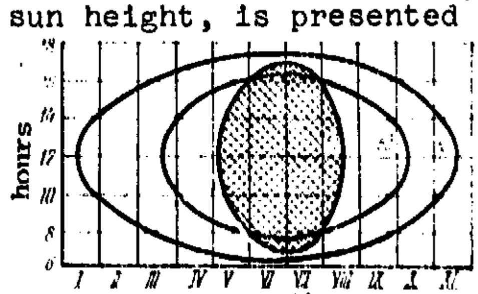


Fig. 1.23 Isoluxes of illumination of the earth at 30,000 lx vs. time of year, day and latitude

The transmission distance is determined by the well-known formula

$$\sqrt{\frac{P_{tr}\sigma_{tr}A_{re}}{4\pi k T^o ...}}, \qquad (1.15)$$

where P_{tr}, σ_{tr} are the power and gain of the onboard radio transmitter antenna, A_{re} is the effective area of the receiving antenna, k is the Boltzmann constant, T° is the absolute radio receiver input temperature, W is the radio receiver noise factor, F is the video frequency band, q is the required signal-noise ratio in a large detail in the radio channel.

The dependence of the probability of interpretation of an image P_{int} on definition N of a frame and the signal-noise ratio q, as well as relations (1.14) and (1.15) permit changing from the planning criteria (P_{int}, L, B, R) to criteria equivalent to them (z^2, q, F, l_f). Selection of the values of the criteria (z^2q, F) depends on the characteristics of the observed object M: area l_0^2 of its optical image on the photolayer, speed of movement v_0, background illumination B_f and contrast k (or drop in illumination ΔB). Therefore, the condition for feasibility of the system (Fig. 1.18) can be written in the form

$$(z^2, q, F, l_f) \left| \begin{array}{l} \in (z^2, q, F, l_f)_{\text{req}}, \\ M \in (l_0^2, v_0, k, B_f). \end{array} \right. \qquad (1.16)$$

The values of the planning criteria required by a technical task are in the right portion of condition (1.16) and, on the left side, the values calculated from the characteristics of system components and object characteristics known a priori.

In planning a broadcast television system and in establishment of GOST 7845-55, a condition of feasibility of the system similar to (1.16) was satisfied. However, the specifics of planning a broadcast television system appear in requirements for matching image quality on screens of television sets with the human visual analyzer. It, in particular, appears in the requirement of the absence of flickering of the frames and creation of a visual illusion of continuity of motion. This matching of the television image with the visual analyzer sharply restricts the range of objects reproducible and efficiency of transmission of information. /50

Predominant in the specifics of planning a space television system is matching the television parameters to the characteristics of the object observed, for the purpose of satisfying condition (1.16). In this case, flickering of the frames is not an unavoidable requirement, since making photographs from the screen, with subsequent interpretation of television photos, is permissible.

1.5 Effect of Linear and Noise Characteristics on Image Quality

In television, it is customary to consider a television system as a multicomponent, two-dimensional filter, converting an optical image $B_0(x, y)$ in a flat light-sensitive layer into an image $B(x, y)$ on a picture-tube screen. The main components of this two-dimensional filter are the following (Fig. 1.24): An optical-electrical converter (transmitting camera) converts the three-dimensional function $B_0(x, y)$ into a function of time $m(t)$(video signal). Video and radio channels are examples of typical filters, operating with a time function and, finally, the picture tube serves as a filter [16], coverting the time function (video signal) into a spatial one $B(x, y)$(image on the picture-tube screen).

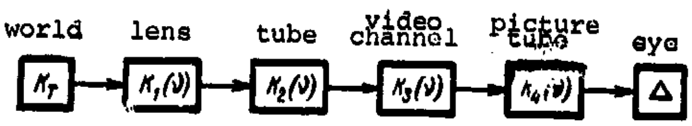


Fig. 1.24 . Linear model of television system

We will consider each of the components listed and the overall television apparatus as a linear, time-invariant filter. This examination permits use of the mathematical apparatus of the Fourier transform for analysis of television apparatus.

In conformance with the mathematical apparatus of the Fourier transform, each component of the linear model of the system is described by a transmission function $K(\omega) = |K(\omega)|/e^{-i\phi(\omega)}$, usually given by the amplitude-frequency $|K(\omega)|$ and phrase-frequency $\phi(\omega)$ characteristics or by a pulse transition characteristic $h(t)$. Both types of estimates are fully equivalent, since functions $K(\omega)$ /51 and $h(t)$ are unambiguously connected by the Fourier transform

$$\left. \begin{aligned} h(t) &= \frac{1}{2\pi} \int_{-\infty}^{\infty} K(\omega) e^{i\omega t} d\omega \\ K(i\omega) &= \int_{-\infty}^{\infty} h(t) e^{-i\omega t} dt \end{aligned} \right| \quad (1.17)$$

where ω equals two πf.

The filter should satisfy the Paley-Viner condition [3]:

$$\int_{-\infty}^{\infty} \frac{|\log K^2(f)|}{1+f^2} \cdot df < \infty. \quad (1.18)$$

Condition (1.18) means that the amplitude-frequency characteristic K(f) of the filter cannot be equal to 0 in a segment of the frequency axis and cannot decay exponentially. Numerical estimates of the amplitude-frequency characteristics K(f) of a low frequency filter, satisfying the Paley-Viner condition, are:

-- Area-equivalent width of characteristic

$$F_{s1} = \int_0^\infty K(f)\,df,$$

-- Power equivalent width of characteristic

$$F_{s2} = \int_0^\infty K^2(f)\,df,$$

-- The width F_0 characteristic by apparent level of decay from 1 to the value K_0, equal, for example, to 0.7 or 0.5 or 0.12: $K(F_0) = K_0$.

Fig. 1.25 Explanation of concept of steric frequency

The method of estimating linear distortions, by means of Fourier analysis is the most highly developed in practice, with reference to one of the television system components, the video amplifier, operating with time functions [17]. However, the mathematical apparatus of the Fourier transform holds true for the function, regardless of whether it is the argument of the functions of time t, space x or two spatial x, y coordinates, or all three coordinates x, y, t. Precisely as for the time harmonic $u(t) = U_0 \sin 2\pi ft$, there exists the concept of time frequency $f = 1/T$(period/sec), for the steric harmonic $B(x) = \frac{B_0}{2}(1 + \sin 2\pi\nu x)$ (Fig. 1.25), /52
there exists the concept of steric frequency $\nu = 1/\lambda$(period/mm).[1]

In scanning devices (camera tube and picture tube), conversion of the steric function into time and vice versa is accomplished. In scanning at a constant rate v(mm/sec), the time

---

[1]One of the first works, in which a Fourier analysis was applied to the steric functions (images), is the widely known work of R. Hartley on information theory [18], created as early as 1928. Together with the term "steric frequency," R. Hartley used, by analogy with optics, the term "wave number." In television, another measure of steric frequency frequently is used: $2\nu\ell$ lines in line of length ℓ.

and steric frequencies are connected by the simple relationship $f = v\nu$.

A Fourier transform for two-dimensional filters, with a pulse transition characteristic,[1] $h(x, y)$, the arguments of which are two spatial coordinates (x, y), has a form similar to that of expression (1.17):

$$\left.\begin{aligned} h(x, y) &= \frac{1}{4\pi^2}\int_{-\infty}^{\infty}\!\!\int K(\omega_x, \omega_y)\, e^{i(\omega_x x + \omega_y y)}\, d\omega_x\, d\omega_y \\ K(\omega_x, \omega_y) &= \int_{-\infty}^{\infty}\!\!\int h(x, y)\, e^{-i(\omega_x x + \omega_y y)}\, dx\, dy \end{aligned}\right\} \qquad (1.19)$$

With circular symmetry (as frequently will occur in optics), two-dimensional Fourier transform (1.19) are reduced to a unidimensional Bessel transform, by means of change to polar coordinates [19]:

$$\left.\begin{aligned} h(r) &= \frac{1}{2\pi}\int_{0}^{\infty} K(\omega_r)\, J_0(\omega_r r)\, \omega_r\, d\omega_r \\ K(\omega_r) &= 2\pi\int_{0}^{\infty} h(r)\, J_0(\omega_r r)\, r\, dr \end{aligned}\right\},$$

where r is the radius-vector, $J_0(\omega_r f)$ is a 0-order Bessel function.

Subsequently, we will use unidimensional (space or time) Fourier transform (1.17), assuming that all the results obtained can be formally distributed, in the case of two (or more) arguments.

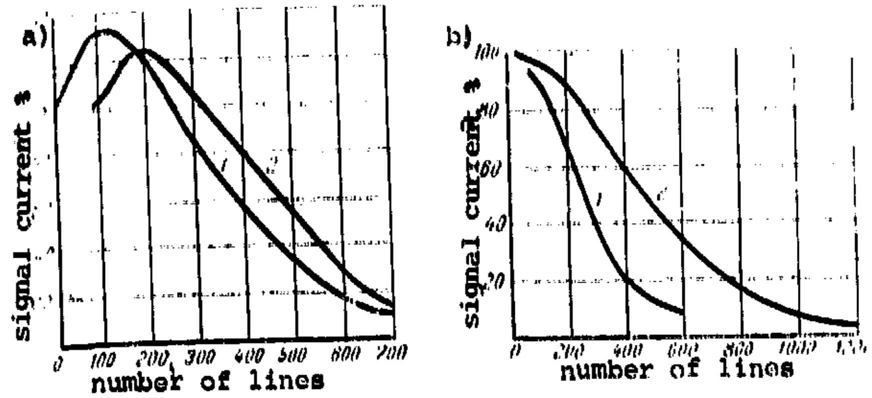
By means of the multiline Foucault globe[2] of maximum contrast, which are contained in the standard test table TIT-0249 [14], /53

---

[1]Because of the still unestablished terminology in various branches of technology (mainly in optics and photography, on the one hand, and in television and radio engineering, on the other), both the pulse transition characteristic itself and its numerical parameters are known by various names. In optics, for example, the two-dimensional pulse transition characteristic h(x, y) is called a scatter diagram.

[2]Globes of black and white lines of equal width were used by Foucault for testing the quality of optical lenses [20].

measurements of the spatial amplitude-frequency characteristic of the camera are made $K_{1,2}(\nu) = K_1(\nu)K_2(\nu)$, where $K_1(\nu)$ is the lens characteristic and $K_2(\nu)$ is the tube characteristic.



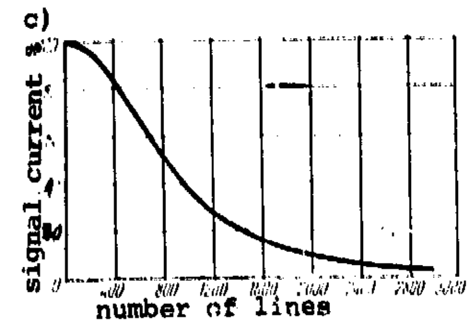


Fig. 1.26 Amplitude-frequency characteristic of television transmitter tubes with lenses: a) superorthicon bulb diameter 76 mm (curve 1) and 113 mm (curve 2); b) vidicon with bulb diameter 25 mm (curve 1) and 40 mm (curve 2); c) slow-scan vidicon with bulb diameter 25 mm and Industar-50 lens.

An example of such characteristics $K_{1,2}(\nu)$ is given in Fig. 1.26, where, instead of steric frequency ν, period/mm, the number of lines $2\nu\ell_r$ (ℓ_r is the length of a line on the photo layer) is plotted. on the abscissa. Characteristics $K_{1,2}(\nu)$ do not disclose limitations as to steric frequency.

A numerical estimate of the resolution of a broadcast television system, by width ν_Δ of the total amplitude-frequency characteristic was presented in work [21] and

$$K_\Sigma(\nu_\Delta) = \Delta, \text{ where } \Delta = 0.12. \qquad (1.20)$$

The readout level $\Delta = 0.12$ in equation (1.20) was selected from the threshold contrast of the eye, which resolves the lines of the globe on the screen of the television set [21, page 126]. Accounting for the effect of camera noise on the screen of the television set, within the framework of this method of calculation of reso- /54
lution, is reduced to an increase in the contrast threshold, i.e.,

an increase in the readout level in equations (1.20) $K_{\Sigma}(\nu_{An}) = A_n$, where $A_n > A$.

The results of allowing for the effect of noise in this manner are illustrated by the calculated graphs in works [22-24][1] (Fig. 1.27). They consist of the conclusion that, with signal-noise ratios above 5, noise practically does not reduce the resolution ν_A, calculated from equation (1.20).

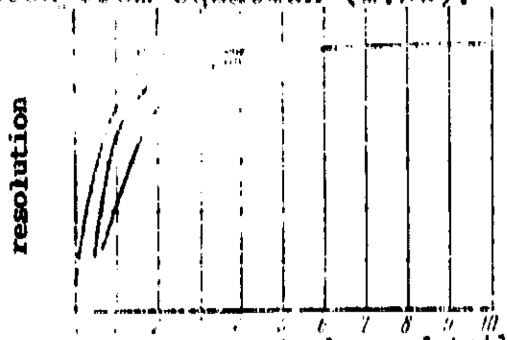


Fig. 1.27 Resolution vs. signal-noise ratio in large detail; 1) from data of work [4]; 2) from data of work [23]; 3) from data of work [22]

We used the method of calculating the resolution by solution of equation (1.20), taking account of the effect of noise within the framework of this equation, in broadcast television, but, in space television, using the resources of video signal contrasting requires another approach, which is set forth in section 2.5.

In broadcast television, the resolving power of visual analyzer is the basis of discretization of the optical image perceived by the television system. The resolving power of the eyes over time permits discretization of the transmission of a natural scene into separate frames. The framerate chosen in television, 25 frames/sec, is sufficient to create the optical illusion of smoothness of motion of objects and to eliminate flickering of the frames. The finite angular resolving power of the eyes permits discretization of a television frame into z lines.[2]

---

[1]An approximation of the amplitude-frequency characteristics by the exponents was used in the calculations, which does not satisfy the Paley-Viner condition.

[2]Visual observation of a frame on the screen of the television set, from a distance equal to five frame heights, corresponds to a viewing angle of about 11°. With the angular resolving power of the eyes equal to one angular minute, the required number of lines in broadcasting is obtained, $z = 11 \cdot 60'/1' = 660$ [1, page 51]. Similar reasoning was used in textbook [2, page 141]. However, the figure presented should be multiplied by 2, by virtue of determinations of the angular resolution from the distance between two black lines separated by a white line [21, p. 49]. Moreover, the angular resolution of the eyes is measured, not by the multiline Foucault globe, but by Landolt rings, which are close to the two-line Foucault globe. This change also can lead to doubling z_{req} (section 2.5). As a result, the calculated figure $z_{req} = 660$ should be quadrupled.

Discretization of the lines into z elements takes place, either in the visual analyzer or by use of a pulse readout in the camera tube. As a result, a television frame can be represented as consisting of $N = z^2$ raster elements, which are squares with sides equal to the line width, in the first approximation. Discrete images, like a mosaic, made up of squares, are widely used as test patterns in television. A test pattern in the form of a checkerboard or the main details of the generally known TIT-0249 can serve as examples [14]. Such a discrete television image can be represented analytically, in the form of a pulse unit vector expansion or geometrically, in form of a N-dimensional vector. It is well-known that any discrete message can be represented by a unit vector expansion /55

$$m(t)=\sum_{k=1}^{N} m_k \varphi_k(t), \quad k=1,\ 2,\ldots,\ N, \tag{1.21}$$

where

$$m_k=\int_{-\infty}^{\infty} m(t)\,\varphi_k(t)\,dt.$$

The set of $\phi_k(t)$ unit vectors, called a system of base functions, satisfies the conditions of orthogonality and standardization:

$$\int_{0}^{T}\varphi_j(t)\,\varphi_k(t)\,dt=\delta_{jk}=\begin{cases}1; & j=k,\\ 0; & j\neq k,\end{cases}$$

where δ_{jk} is the Kroneker symbol.

Spectral unit vectors (i.e., the sines or cosines in Fourier series or a Fourier integral) and pulse unit vectors are most widely used. Among the pulse unit vectors, unit vectors in the form of nonoverlapping, rectangular pulses of duration Δt are the most graphic (Fig. 1.28a)[3, page 209]

$$\varphi_k(t)=g(k\Delta t)=\begin{cases}\dfrac{1}{\sqrt{\Delta t}}; & (k-1)\Delta t<t\leq k\Delta t,\\ 0 \text{ at remaining } t,\end{cases} \tag{1.22}$$

where

$$k=1,\ 2\ \ldots,\ N,\ N=\frac{T}{\Delta t}.$$

It is easy to verify that the set of N square pulses (formula 1.22) satisfies the conditions of orthogonality and standardization (pulse energy equals unity). A series expansion of a discrete message by square pulse unit vectors.

$$m(t)=\sum_{k=1}^{N} m_k\, g(t-k\Delta t), \tag{1.23}$$

where $m_k = \int m(t) g(t - k\Delta t) dt$

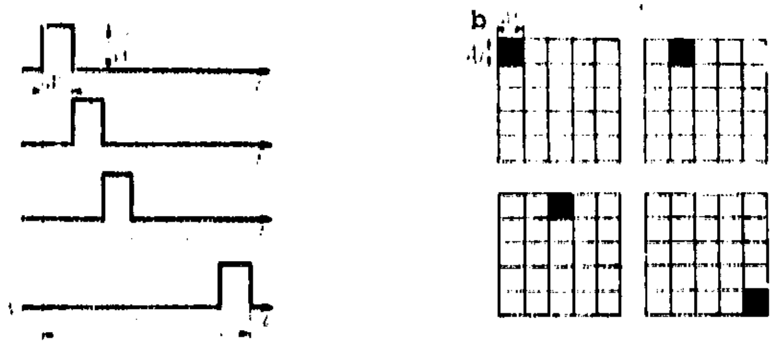


Fig. 1.28 System of square pulse unit vectors /56

What has been said for a discrete time function m(t) holds true for the spatial function m(x, y). Spatial unit vectors g(kΔx, jΔy) in this generalization, will be squares of area ΔxΔy (in which Δx = Δy), which are shifted relative to one another by an amount Δx and Δy. Fig. 1.28 illustrates spatial unit vectors for a system containing 25 square spatial vectors (squares). A discrete, two-tone image, consisting of 25 square elements, is presented in Fig. 1.29.

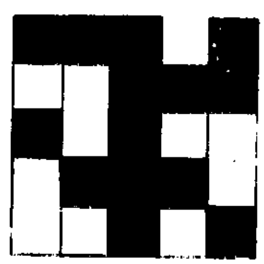


Fig. 1.29 Discrete, two-tone image of 25 square elements

Coefficients m_k express the tone brightness (gradations) of the squares. In communications theory, not only is the analytical representation of a discrete message m(t) used, in the form of a sum of N terms (formula [1.21]), but a geometric representation of it, in the form of an N-dimensional vector, the coordinates of which are the coefficients m_k of sum (1.21) $m = (m_1, m_2, \ldots m_N)$.

Geometrically, we represent a discrete television frame, of N elements in the (x, y) plane, i.e., by a two-dimensional space, by a vector (or point) in N-dimensional space. In this case, a complex object (for example, a television frame) in two-dimensional space is replaced by a simple object (vector or point) in multidimensional space [6, page 438].

Let us examine the properties and manifestation of noise in a linear television system.

The decisive effect of noise on evaluation of the quality of diverse systems was clearly formulated in information theory [4-7].

Sources of television system noise are shown in Fig. 1.30. The principal source of noise in transmitter cameras is the electron flux of the tube or the first tube of the video amplifier. Noise of this origin usually is called shot noise. /57 Shot noise is a microscopic manifestation of the discrete nature of the electron flux. This means that each "little sound" observed, for example, in an oscillograph of the noise process, is a result of the action of, not a single electron, but of a quite large number of electrons.

A mathematical model of noise is a steady-state random process n(t), satisfying the condition of regularity [26]. The paramount statistical characteristics of steady-state random process n(t) are the first order moment, the mean value of $\overline{n(t)}$, and the second order moment, correlation function $\psi_m(\tau)$.

A requirement for a steady-state means that the video signal autocorrelation function $\psi_m(\tau)$ and, consequently, its spectral power density $S_m(\omega)$ are invariant over time. As is well-known, the autocorrelation function is defined by the expression

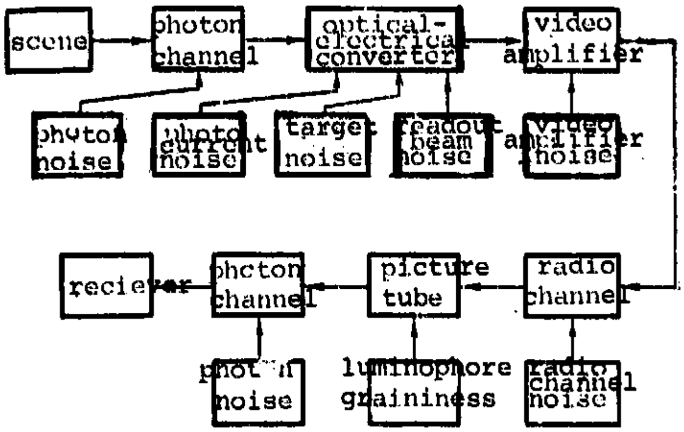


Fig. 1.30 Structural diagram of television system with noise sources

$$\psi_m(\tau) = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T} m(t)\,m(t-\tau)\,dt.$$

The spectral power density is a simple Fourier transform of the autocorrelation process, i.e.,

$$S_m(\omega) = \int_{-\infty}^{\infty}\psi_m(\tau)\,e^{-i\omega\tau}\,d\tau,$$

$$\psi_m = \frac{1}{2\pi}\int_{-\infty}^{\infty} S_m(\omega)\,e^{i\omega\tau}\,d\omega.$$

The spectral density $S_m(f)$ /58 is understood from the expression for video signal power

$$P_m = \psi_m(0) = \int_{-\infty}^{\infty} S_m(f)\,df = \lim_{T\to\infty}\frac{1}{2T}\int_{-T}^{T} m^2(t)\,dt.$$

In this formula, the quantity $\psi_m(0)$ is expressed in watts and $S_m(f)$ in watt-seconds. Function $m^2(t)$ is the mean square of the voltage, in volts per resistance of one ohm. Since the autocorrelation function $\psi_m(\tau)$ carries information on the statistical connections in the video signal, the spectral density $S_m(\omega)$ contains similar information. In the absence of statistical connections in the video signal, the autocorrelation function equals the δ function, i.e., $\psi_m(\tau) = \delta(\tau)$, and the spectral density is independent of frequency, i.e., $S_m(f)$ = const. The presence of statistical connections in the video signal causes expansion of the autocorrelation function or a drop in the spectral density in the high frequency region.

In distinction from pulses, having a finite duration and, as a consequence, a finite energy, random, steady-state process n(t) does not tend towards zero as $t \to \infty$. Therefore, the noise energy equals infinity:

$$\int_{-\infty} n^2(t)\,dt = \infty.$$

However, the noise power n(t) is a finite quantity, for which a method of measurement is known. This permits the concept of spectral density of the power $S_n(f)$ to be introduced, the integration of which gives the value of the noise power [26, 27]

$$P_n = \psi_n(0) = \int_0^\infty S_n(f)\,df.$$

Measurement of the noise power and spectral density is widespread in television practice. Usually, the ratio of the peak video signal power $U^2_{c\ max}$ (the square of the voltage spread between the black and white control levels at a resistance of one ohm) to noise power is measured [14]:

$$q^2 = \frac{U^2_{c\ max}|K(0)|^2}{\int_0^\infty S_n(f)\,|K(f)|^2\,df},$$

where $|K(f)|^2$ is the square of the amplitude-frequency characteristic of the part of the system through which noise $S_m(f)$ passes.

Similarly, the peak signal-noise ratio q determines the signal-noise ratio in the problem of detecting a video signal on a background of noise [28].

To detect a video signal, i.e., to obtain a response to the question as to whether there is a video signal or not, with an estimate of the television system quality which is too low, is completely unsuitable for television. Therefore, parameter q usually is /59 used in broadcast television technology for another task, evaluation of the visibility of noise on a picture-tube screen. Since the quantity $U_{c\ max}|K(0)|$ is established as equal to the dynamic (voltage) range of the picture tube, the quantity which is the reciprocal of the peak signal-noise ratio determines which portion of the dynamic range the root mean noise value occupies. Experiment has shown that there is such a limit to the peak signal-noise ratio Q_{lim} value, exceeding which $q > Q_{lim}$, the noise becomes practically unnoticeable on the television set screen and, at values $q = q_{lim}$, the noise is scarcely noticeable. The value of q_{lim} fluctuates from 31 to 49 db (i.e., approximately from 30 to 300 times)[14].

However, the harmful effect of noise appears, not only and not so much in its visibility, irritating the observer, as in masking by it of a useful signal. Noise is a false signal, masking the useful video signal and, thereby, prevents obtaining videoinformation from the objects being studied in the process of observation of television images by man. The masking effect of noise on small details of an image will be considered in section 2.5. It should be noted here that the amount of useful videoinformation extracted by an observer from a television image depends on both the means of noise control used in the television system and on the degree of perfection of the noise control mechanism established in the visual analyzer.

Fig. 1.31 Amplitude-frequency characteristic of narrow-band filters

An experiment was carried out to evaluate the ability of the visual analyzer to filter out a segment of a three-dimensional sinusoid on a noise background [28]. It consisted of measurement of the value of the signal-noise ratio $q = q_{th}$, corresponding to the visual detection threshold, as a function of the sinusoidal signal frequency, at a given value of the resonance frequency f_r of the filter, through which white noise passed. The measurement was carried out in the following manner. White noise was passed through one of the pass-band filters with resonance frequency f_r (Fig. 1.31), it was mixed with a sinusoidal signal frequency f_c and supplied to the input of the video amplifier of a television set with a 47LK1B picture tube. In this case, an image in the form of a band appeared on the television set screen (Fig. 1.32). The ratio of the effective value of the sinusoid to the root mean value of the narrow-band noise q was measured at the picture-tube input. By increasing the effective value of the sinusoidal signal, the observer established the signal detection threshold on the background of narrow-band noise, at which he could count the number of bands on the picture-tube screen. The relation found is presented in Fig. 1.33. It follows from analysis of curves 1, 2 and 3 that the the visual analyzer, in the region of low steric frequencies, distinguishes the sinusoidal signal on the narrow- /60
band noise background better, the greater the spread between frequencies f_c and f_r (the threshold signal-noise ratio q_{th} forms a maximum when f_c coincides with f_r). In this frequency region, the visual analyzer is similar to a filter, automatically adjusting on the sinusoidal signal frequency. In the region of high steric frequencies, attenuation is observed in the ability of the visual analyzer to filter out the sinusoidal signal from the noise. The maximum of curve 3 in Fig. 1.33 becomes flat, and curves 4 and 5 increase monotonically with increase in frequency f_c. This can be explained by the fact that, with increase in frequency f_c, the visual analyzer gradually loses the ability to adjust on the signal frequency, since its amplitude-frequency characteristic expands. /61
Beginning with a certain steric frequency of the sinusoidal signal, the amplitude-frequency characteristic of the visual analyzer does not readjust. It should be noted that the bending curves represented in Fig. 1.33 by a dashed line corresponds to a monotonic increase

in the threshold of visual detection of a sinusoidal signal on a background of wide-band Gaussian noise (white noise, passing through a broadcast television system and picture-tube channel), with increase in sinusoid frequency f_c (see curve 1 in Fig. 1.34). For comparison, curve 2 is given in Fig. 1.34, showing the weak dependence of the sinusoidal signal detection threshold on frequency, on background of wide-band Gaussian noise, during visual observations, not of a picture-tube screen, but of an oscillograph screen.

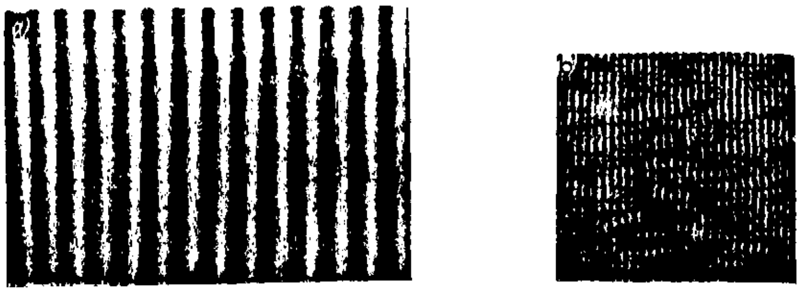


Fig. 1.32 Image of steric sinusoid on video monitor screen: a) without noise; b) on a background of narrow-band noise

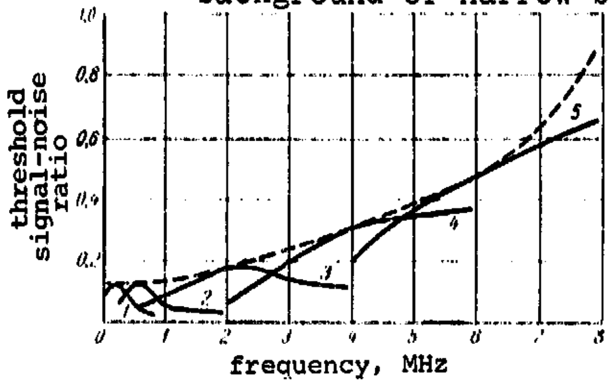


Fig. 1.33 Curves of detection threshold of sinusoid at frequency f_c on background of narrow-band noise, passing through filter with resonance frequencies f_r of 1) 0.2 MHz, 2) 0.5 MHz, 3) 2 MHz, 4) 4 MHz 5) 6 MHz

For an estimate of the ability of the visual analyzer to suppress various sections of the white noise spectrum in the process of resolving fine details, measurements were made in an experimental unit, a structural diagram of which is presented in Fig. 1.35. The signal sensor generated a two-pulse signal, which was mixed with narrow-band noise. This narrow-band noise was formed by means of extraction of a spectral section of white noise, by means of one of the filters in a filter unit. The amplitude-frequency characteristics of the filters, with resonance at frequency f_r, is represented in Fig. 1.31. The mixture of the two-pulse signal and narrow-band noise with frequency f_r was supplied to an oscillograph and a video monitor (VM), mounted on the base of a television set with a 47LK1B picture tube. Photographs obtained from the VM screen are introduced in Fig. 1.36. The experiment consisted of having an observer examining television images of two lines on a background of narrow-band noise from a fixed distance (600 or 1250 mm), and the distance between pulses was increased, by regulating their movement until the

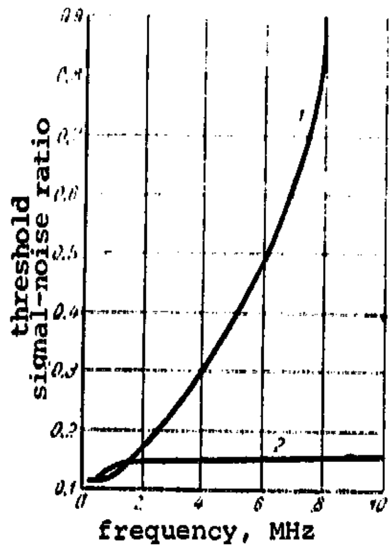


Fig. 1.34 Threshold signal-noise ratio in detection of sinusoid in Gaussian noise: 1) on television set screen; 2) on oscillograph screen

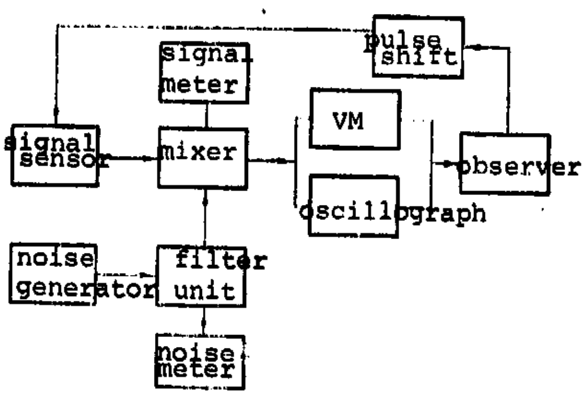


Fig. 1.35 Structural diagram of measuring unit for study of resolution of two lines on noise background

moment of appearance of resolution of the two lines. As a result of the observation, a curve of the resolution interval τ (μ sec) of the two pulses vs. resonance frequency of the pass-band filter forming the narrow-band noise was obtained (Fig. 1.37). The following can be concluded from the figure:

-- All spectral sections of the noise interfere with resolution of the two lines; /62

-- A narrow-band noise with higher frequency f_n, i.e., the high-frequency section of the noise spectrum, masks the lines more strongly.

The latter conclusion is based on the fact that noise pattern acquires a finer structure, approaching the dimensions of the lines. This factor, in combination with the drop in the amplitude-frequency characteristic of the visual analyzer and the picture tube in the high frequency region (the power of the high-frequency sections of the noise spectrum chokes more strongly) leads to the appearance of a weak maximum in the Fig. 1.37 curves. With increase of distance from the screen from 600 to 1250 mm, the amplitude-frequency characteristic of the subsystem picture tube plus visual analyzer drops more sharply in the high-frequency region, which causes displacement of the maximum to the lower-frequency region and deterioration of resolution.

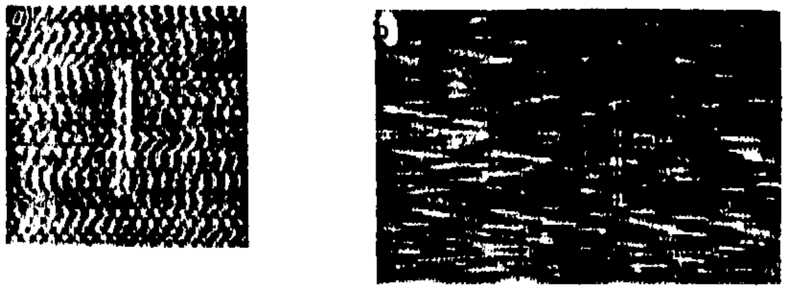


Fig. 1.36 Two lines on a background of narrow-band noise (photograph from videomonitor screen: a) f_r = 4 MHz, b) f_r = 6 MHz

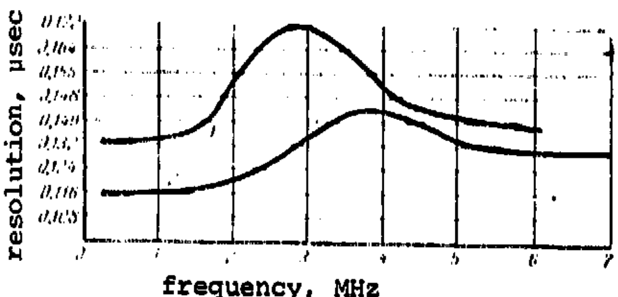


Fig. 1.37 Resolution interval of two lines τ vs. mean frequency f_r of narrow-band noise, at examination distances of 1250 mm (1) and 600 mm (2)

2. FUNDAMENTALS OF TELEVISION THEORY

2.1 General Information

Television theory is based on theory of optimum reception and information theory. Inclusion of the theory of optimum reception is caused by the fact that a television system contains, not only a radio receiver, in the usual sense of of this term (in broadcast television, this is the television set), but a specific receiver of electromagnetic waves of the light range, the television camera, on optimum design of which the light sensitivity of the system and quality of the television image depend.

The measure of information is used in television for evaluation of the technical image quality. The connection of quality of transmission of an image with the degree of information was noted in the work of Hartley in 1928 [18].

It is well-known that, in the work of Kotel'nikov in 1947[4], a theory of noise proof (optimum) reception was set forth, without drawing on the measure of information. Information theory was set forth in the work of Shannon in 1948 [6], from the point of view of noise proof coding. Elimination of the disconnections in the accounts of the two theories mentioned became the purpose of work [3, pp. 5-9]. The requirements of planning space television systems also need elimination of these disconnections.

Let us examine the basic concepts of information theory and theory of optimum reception. The basic aspects of information theory and optimum reception theory were formulated, with reference to discrete messages and, first and foremost, to a language text.

In comparison with energy, the concept of information is incomparably more complicated, since it includes semantic and emotional aspects. Information is such a complex concept that the apparatus of modern mathematics obviously is inadequate for creation of a quantitative measure of information. Another, narrower, specialized concept of information arose in communications theory, to which the term "nonsemantic information" can be applied. /65
Extraction from the broader, but mathematically unformalized concept of information of a narrower, but formalized concept of nonsemantic information was a revolutionary event in the creation of information theory.

Information theory was first worked out by Nyquist in 1924 [6] and Hartley in 1928 [18]. These works responded to the requirements for improvement of communication transmission systems, first and foremost, systems of transmitting a text by telegraph.

Leaning on the structure of the text and its transmission in Morse code, the authors [36, 18] essentially used a model of discrete communications, which was represented in the form of a sequence of N symbols (letters, numbers, elements)

$$(m_{i1}, m_{i2}, \ldots, m_{ik}, \ldots, m_{iN}), \quad i = 0, 1, \ldots, M - 1. \tag{2.1}$$

Each of the symbols m_{1k} has a set S of possible values, an alphabet:

$$m_{ik} \in (a_1, a_2, \ldots, a_S).$$

It had been noted as early as work [36] that the number of possible sequences $M = S^N$. An important feature of this work was the assertion that two codes (sequences) should be considered equivalent in difficulty of their transmission through a channel, if the number of possible sequences is identical, i.e., the following condition is satisfied [36, p. 343]

$$S^N = \text{const} \text{ or } N \log_2 S = \text{const}. \tag{2.2}$$

However, it was not stated in this work that expression (2.2) can serve as a measure of information. The concept of information rate was introduced, and it was proved that, for a system transmitting a given number of symbols per unit of time, the rate [36, p. 343] $v = c \log_2 S$ where c is a constant.

The concept of nonsemantic information and quantitative measurement of it was most clearly set forth in work [18]. For an evaluation of a transmission system, "psychological," i.e., semantic and emotional, factors had to be excluded from the concept of information. This approach meant substitution of a real, discrete message (text), which is semantic by its nature, by an abstract, nonsemantic model, in form of that sequence (2.1), in which each symbol m_{1k} is the result of a random selection from the alphabet. The number of such nonsemantic messages was determined by the quantity (2.2). A quantitative measure of information is proportional to the number N of primary choices of symbols from the alphabet:

$$H = \log S^N = N \log S. \tag{2.3}$$

Formula (2.3) shows that the measure of information is the logarithm of the number of possible sequences of symbols. It is clear from it that, for messages with an identical alphabet (i.e., logS = const), the measure of information H is proportional to the number of symbols in the message, i.e., to the number of letters in the text.[1] /66

[1]An evaluation of a book by number of typographical symbols (one author index contains $4 \cdot 10^4$ typographical symbols) can serve as an illustration of the use of the measure of nonsemantic information for evaluation of difficulty of storage of language texts.

Subsequently, the base two logarithm was selected as the measure of information. With this precise definition, a unit of nonsemantic information is one binary unit (bit), obtained from the selection of one of two equally probable symbols:[1]

$$H = N \log_2 S, \text{ binary units} \tag{2.4}$$

Subsequent development of the measure of information involves deepening the statistical model of communications and drawing on the mathematical appar tus of probability theory [4-7].

In the basic work of Kotel'nikov in 1947 on the theory of noise free (optimum) reception [4], a mathematical model of a discrete message m was used, in the form of a set (ensemble) M of sequences (2.1) of N random values m_{ik} (i.e., N-dimensional random value).

Analytical representation of this model is the sum

$$m_i(t) = \sum_{k=1}^{N} m_{ik}\varphi_k(t), \quad i = 0, 1, 2, \ldots, M-1, \tag{2.5}$$

where
$$m_{ik} = \int_{-\infty}^{\infty} m_i(t)\varphi_k(t)\,dt$$

are random, unidimensional quantities and $\phi_k(t)$ are unit vectors.

In this work, the geometric representation of a model of a discrete communication was introduced, as a random vector in N-dimensional space with unit vectors.

$$\{\varphi_k(t)\}: \vec{m}_i = (m_{i1}, m_{i2}, \ldots, m_{iN}),\ i = 0, 1, 2, \ldots, M-1.$$

Deepening the representation of the possibility of substitution of real messages by statistical models, of course, should have led to establishment of a connection of measure of information with the characteristics of random values. Such a connection was established in the works of Shannon [6] and Viner [7] in 1948. It was shown in work [6] that measure of information (2.4) is the maximum value of the entropy of the probability distribution of unidimensional random values, calculated in the partial case of equally probable symbols m_{ik} from the alphabet $(a_1, a_2, \ldots, a_S)$ and the independence of neighboring symbols. For the probability distribution $P(a_j)$ of symbols a_j, known a priori, the entropy in /67
the symbol

$$H_1(m_{ik}) = -\sum_{j=1}^{S} P(a_j)\log_2 P(a_j), \frac{\text{binary unit}}{\text{symbol}}$$

---

[1]The provisional nature of the concept of nonsemantic information can be illustrated by the fact that the answer to the question of the tormented Hamlet, "To be or not to be," could be given by him with a total of only one binary unit of information.

The a priori entropy reaches the maximum with equal probabilities:

$$\max H_1(m_{ik}) = \log_2 S \text{ at } P(a_i) = 1/S$$

Ensemble (2.5) is composed of N independent, random, equally probable values, containing M equally probable sequences. The entropy of this ensemble

$$H(m) = \sum_{i=1}^{N} H_1(m_{ik}) = NH_1(m_{ik}).$$

The maximum value of the entropy of the ensemble coincides with formula (2.4):

$$\max H(m) = N \max H_1(m_{ik}) = N \log_2 S = \log_2 M. \qquad (2.6)$$

This coincidence confirms that the entropy can serve as a quantitative measure of the possibility of selection or indeterminacy, i.e., serve as a measure of the amount of information, which is more general than the measure of information (formula 2.4). A decrease in entropy from the maximum value was caused by unequal probability of selection of symbols from the alphabet and, chiefly, by the presence of statistical connections between the symbols in the message. This decrease is evaluated by means of the statistical excess β =

$$1 - H(m)/\max H(m); \quad H(m) = (1 - \beta) \max H(m).$$

While, according to Nyquist and Hartley, the number of texts of N letters $M = S^N = 2^{\max H}$, according to Shannon, by means of coding, taking account of the statistical connections, this number can be shortened to $M_\beta = 2^{(\beta-1)\max H}$, $M_\beta \leq M$.

It is clear from daily experience that the number M_c of "intelligent" texts is incomparably smaller than M (i.e., $M_c \ll M$). It is evident that the prospects of compressing the text (as with other discrete messages) depends on the ratio of the values M_β and M_c. Shannon considered that, by means of expanding the statistical connections between letters in an artificial language, a whole series of sequential approximations to a natural language can be achieved [6, p. 253]. However, in no way did he confirm the final results of these approximations (i.e., the possibilities of an artificial language and a natural one coinciding [6, p. 255].

In the well-known work [5] of Kolmogorov (1956), concerning an estimate of the number of intelligent texts ($M_c \ll \overline{M}$), he notes:

"The full use of this fundamental possibility of 'text compression,' of course, lies beyond the limits of what can be accomplished, by means of any system of stenography or coding of texts, following quite simple formal rules: The pattern of the structure of a real language text will scarcely be completely formalized at any time" [5, p. 71]. This means, from the small size of quantity M_0, no conclusion can be drawn as to the smallness of the quantity M_e, which could serve as an estimate of the prospects of statistical methods of text compression, just like other types of communication[1] /68

The following precise definition of the concept of information was connected with taking account of noise and definition of a signal. A signal is defined as a physical carrier of information on a message. For example, electromagnetic radiation or an electric current can serve as such a carrier. In the microscopic aspect, these carriers of information are quantum (photon) or electron fluxes. Fluctuations in the number of photons or electrons are manifested microscopically, in the form of photon noise or current shot noise. Therefore, any signal is a mixture of communications and noise. Since noise, in distinction from communications, is devoid of intelligent aspects, it is quite completely reflected by a mathematical model, in the form of a random function.

Information on a message is withdrawn by a receiver from signal r which is the sum of the message m and noise n. Consequently, a quantitative measure of information should answer the question, how much information I(r, m) is contained in signal r = m + n, relative to message m. It was shown in work [6] that the amount of information for a discrete message m equals the decrease in entropy:

$$I(m+n, m) = H(m) - H_r(m). \tag{2.7}$$

where $H_r(m)$ is the provisional entropy, called unreliability.

Formula (2.7) shows that, only in the idealized case of complete suppression of noise [i.e., $H_r(m) = 0$] and exact reception of a message, does the amount of information equal the entropy: I(m, m) = H(m).

In the general case, the amount of information equals the decrease in entropy from an a priori value H(m), not to zero, but to an a posteriori value $H_r(m)$. The quantity $H_r(m)$ expresses the residual indeterminacy, due to the presence of noise.

In this manner, the concept of nonsemantic information leads to quantitative measurement of it, for discrete messages, express-

[1]This question was examined in article [37], with reference to television communications.

ible by the difference in a priori and a posteriori values of the entropy. This result contains an element of surprise. This is that it was completely unclear, whether or not messages differing in meaning, for which a certain numerical measure was identical, can actually be considered to be equivalent in difficulty of transmission through communication channels and storage in memory devices [5, p. 75]. It turned out that such a measure exists and permits solution of a broad class of practical problems.

The established formula for calculation of the amount of information discloses still other operations, which must be carried out on the signal, for the purpose of reproduction of a useful message. These operations are formulated in optimum reception /69 theory [3, 4], which uses the same statistical models of communication of noise and signal as in information theory. The idea of optimum reception is most simply set forth, by means of a geometric representation of a message and noise.

Let us briefly examine the basic aspects of the theory of optimum reception of discrete messages [3, 4].

A signal enters the receiver input, which is the sum of a discrete message and noise:

$$m_i(t) + n_\infty(t), \tag{2.8}$$

where $m_i(t) = \sum_{k=0}^{N} m_{ik}\psi_k(t),\ i=0, 1, 2, \dots, M-1;\ n_\infty(t) = \sum_{k=1}^{\infty} n_{\infty j}\psi_j(t),$

in which $m_{ik} = \int_{-\infty}^{\infty} m_i(t)\psi_k(t)\,dt,\ n_{\infty j} = \int_{-\infty}^{\infty} n_\infty(t)\psi_j(t)\,dt.$

For simplicity, we consider the noise to be white, having a Gaussian distribution, with zero mean value and dispersion $S_n/2$; [3, p. 215]. Since noise is a geometric, random vector of infinite dimensions n_∞, the input signal r(t) will be a random vector of infinite number of dimensions:

$$\vec{r}_\infty = \vec{m}_i + \vec{n}_\infty, \tag{2.9}$$

where $\vec{m}_i = (m_{i1}, m_{i2}, \dots, m_{iN}),\ \vec{n}_\infty = (n_{\infty 1}, n_{\infty 2}, \dots).$

This is the formulation of the problem in optimum reception theory. Message ensemble (N-dimensional vectors) $\{\vec{m}_i\}$ is known a priori at the transmitting and receiving ends. Because of noise, the signal (vector $\vec{r}_\infty$) does not exactly coincide with a single one of the messages of the ensemble $\{\vec{m}_i\}$. Making a choice from the message ensemble, the transmitter transmitted message $\vec{m}_i$: $\vec{r}_\infty$ enters the receiver input. Using the results of measurement of vector $\vec{r}_\infty$ and the a priori information, the receiver should select vector

$\vec{m}_i$ from ensemble $\{\vec{m}_i\}$, which was transmitted (i.e., reproduce the message transmitted).

We list the information, which is considered to be known a priori in receiving:

1. N-dimensional space of discrete message, i.e., the set of N unit vectors $\{\phi_k(t)\}$;

2. The entire ensemble M of expected messages, i.e., vectors $\{\vec{m}_i\}$ themselves and the distribution pattern of the a priori message probabilities $P\{\vec{m}_i\}$.

For simplicity in the presentation, we will consider that all/70 messages of the ensemble are equally probable:

$$P(m_i) = \frac{1}{M}, \; i = 0, 1, 2, \ldots, M-1. \tag{2.10}$$

Then, by formula (2.6), the entropy of the ensemble $H(m) = \log_2 M$, binary units.

Receiving a message consists of selection of one vector of the known ensemble $\{\vec{m}_i\}$, on the basis of processing of random input vector $\vec{r}_\infty$, in the presence of the a priori information listed.

According to Kotel'nikov [4, p. 33], the criterion of correctness of choice is the maximum a posteriori probability, which, by condition (2.10), is simplified to the minimum distance between vectors. The process of choosing a vector from ensemble $\{\vec{m}_i\}$ is a process of adopting a solution as to which message was transmitted.

The ideal (optimum) receiver of Kotel'nikov carries out the following operations:

1. He measures the projection r_{ik} of random vector $\vec{r}_\infty$ in N-dimensional space of the message, i.e., he projects the vector on the unit vectors $\{\phi_k(t)\}$:

$$r_{ik} = \int_{-\infty}^{\infty} [m_i(t) + n_\infty(t)]\,\varphi_k(t)\,dt = m_{ik} + n_k, \; k = 1, 2, \ldots, N. \tag{2.11}$$

A set of N projections r_k defines vector $\vec{r}_i$, which i is a geometric realization of a signal at the receiver output:

$\vec{r}_i = \vec{m}_i + \vec{n}$, where $\vec{r}_i = (r_{i1}, r_{i2}, \ldots, r_{iN})$, $\vec{n} = (n_1, n_2, \ldots, n_N)$.

It is evident that vector $\vec{r}_1$ carries all the information of the transmitted message $\vec{m}_1$, but with distortions due to noise; infor mation of vector $\vec{r}_1$, "degeneration" of the noise vector takes place, since vector $\vec{n}_\infty$ of infinite number of dimensions is projected in N-dimensional space, which gives N-dimensional vector n as the realization of the noise;

2. He calculates the distance in space of the communication between each of the vectors and the plotted vector

$$d_i = |\vec{r}_1 - \vec{m}_i|^2 = \sum_{k=1}^{N}(r_{1k} - m_{ik})^2.$$

Distance d_1 serves as material for making a decision: That vector $\vec{m}_1$, which is characterized by the minimum distance, is selected as the reproduced message. The rule of this solution is written in simple form

$$\min_{(i)} |r_i - \vec{m}_i|^2. \qquad (2.12)$$

In accordance with the two operations specified, the receiver /71 can be represented as consisting of two devices: A storage device and a decision-making one (Fig. 2.1). The operation of projection of vector $\vec{r}_\infty$ in the message space can be realized, by means of a set of N filters matching the unit vectors of the message, if [3, p. 217]:[1]

$$\phi_k(t) = 0 \text{ at } t < 0 \text{ and } t > T.$$

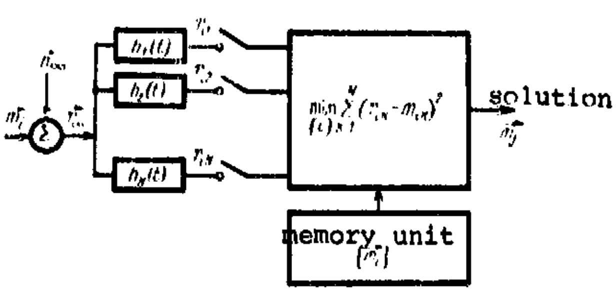


Fig. 2.1 Diagram of optimum receiver of discrete messages

Using the a priori information on a set of unit vectors $\{\phi_k(t)\}$, the pulse characteristics $h_k(t)$ of the filters can be selected as delayed and mirror-reflected copies of the unit vector:
$h_k(t) = c\phi_k(T-t)$, where c is a constant. The response at the matched filter output

$$r_k(t) = \int_0^t r_\infty(\tau)\, h(t-\tau)\, d\tau = \int_0^t r_\infty(\tau)\, \varphi_k(T - t + \tau)\, d\tau.$$

---

[1]Another possibility of realization is used in a correlation receiver, which contains N multipliers and integrals [3, p. 216].

At moment t = T, the value of the response

$$r_k(T) = \int_0^T r_\infty(t)\varphi_k(t)dt = r_k = m_{ik} + n_k.$$

In this way, at the output of N matched filters, we obtain N projections of vector $\vec{r}_i$ (of the output signal).

A matched filter, as is well-known, serves as an ideal pulse energy storage device. The operation being considered is no other than realization of the so-called build-up method. Therefore, we call the device the storage device of the optimum receiver. The storage device fulfills the major function of noise control. By means of signal storage, the useful information contained in the /72 input signal mixed with noise is extracted to such an extent, that it beomes possible to select the message from ensemble $\{m_i\}$.

The simple role of the method or principal of storage, in creation of highly sensitive electronic television systems is well-known (see editor's note on page 770 [2]). In television, this principal usually is set forth in the historical aspect of appearance of inventions putting it into practice in an electronic instrument. In work [4], a mathematical description of the operation being discussed was given, without emphasizing the role of the storage principle. It is evident now that the ideal receiver of Kotel'nikov includes this principle (true, as long as applied to receiving discrete messages), in its geometrical interpretation as a projection of vector $\vec{r}_\infty$ in a message space of a finite number of dimensions.

Synthesis of a receiver storage device of N filters, matched with the unit vectors, provided coincidence of the space of the output signal $\vec{r}_i$ with the space of the input message $\vec{m}_i$. This permits changing to the following optimum reception operation, which takes place in the decision device of the receiver (Fig. 2.1):

-- It calculates the distance d_i between vector $\vec{r}_i$ of the output signal and each of the a priori known vectors $\vec{m}_i$:

$$d_i^2 = |\vec{r}_i - \vec{m}_i|^2 = \sum_{k=1}^{N} |r_{ik} - m_{ik}|^2, \quad i = 0, 1, 2, \ldots, M-1;$$

-- A choice is made of one of the a priori known vectors $\vec{m}_i$, in accordance with formula (2.12), i.e., by the minimum distance.

The a priori information should be set into the receiver structure. For this, the receiver should have an operational memory unit, with a specific capacity (Fig. 2.1). Calculation of the distances between vector $\vec{r}_i$ and each of the vectors $\vec{m}_i$ involves the receiver resorting to the memory. From the calculated distance, the minimum value of d_i^2 should be found, which determines the choice of vector m_i, i.e., a decision is made. The time expended in the calculation determines the decisiontime, which will depend on the memory capacity and rate of examination of the stored a priori information: $T_{res} \sim C_{rm} V_{ob}$, where C_{rm} is the receiver memory capacity and V_{ob}, binary unit/sec is the rate of examination of the information in the memory unit.

We draw attention to the fact that the ensemble of pure messages unmixed with noise $\{\vec{m}_i\}$ is stored in the operational memory of the receiver, by selection of one of which, receiving (reproduction) of the message is completed. The reproduced message will be the same one unmixed with noise as the message transmitted $\vec{m}_i$. Because of the presence of noise, the decision device can make an /73
error and select, not message $\vec{m}_i$, but, let us say, $\vec{m}_i-1$ or $\vec{m}_i+1$. However, in any case, the reproduced message will be noise free.

The specifics of the process of making a decision appear here: The choice is made, according to vector $\vec{r}_i$, containing a message on a noise background, but, after choice, the noise-free message is reproduced. Because of the presence of noise, making a decision on the choice of message $\vec{m}_i$ from ensemble $\{\vec{m}_i\}$ is characterized by the probability of correct reception of less than unity and a probability of error greater than zero. The greater the distance between the vectors $\{\vec{m}_i\}$ and the less the length of the noise vector, the less the probability of error. For practically reliable receiving of a message, it is not obligatory that a theoretical estimate of the probability of error equal zero. Experience in receiving a text by telegraph or everyday experience in reading texts confirms this.

Comparing the basic concepts of information theory and optimum reception theory set forth above, their similarity can be noted, in the fact that the idea of selection of a message from an ensemble is used in both theories, true, from somewhat different points of view. A quantitative measure of the possibility of choice is used in information theory for evaluating indeterminacy. Attention is stressed in receiving theory to making a choice as a decision-making process.

A measure of information is synthesized, by means of an integral estimate of the probability distribution pattern of the entropy. Such an estimate is statistical in nature, but it is not probabilistic. The decision-making rule (formula 2.12) introduced above also is not probabilistic. However, this is only the simplest partial rule. Criteria were suggested in work [4], according to the maximum a posteriori probability. Subsequently, the probabilistic approach to study of the decision-making process led to extensive use of various probability criteria encompassed by statistical decision theory [3, 38].

Optimum reception theory enriches the conception of the process of obtaining information and, in particular, emphasis on the importance of a priori information in choosing a message.

2.2 Bringing an Optimum Receiver of Discrete Messages into Being

We turn to the generalized structural diagram of a communications system, which is generally accepted in communications theory [6, p. 245](Fig. 2.2). In the diagram, the receiver is separated from the recipient making a decision on the message. There are two definitions of a receiver: Including a decision-making device /74 (as in section 2.1) and without a decision-making device. We examine the possible reason for the presence of two definitions below and, until then, we turn our attention to the fact that the structural diagram in Fig. 2.2 permits coding of a pure, noise-free message in the transmitter. The signal from the transmitter output is subject to degradation by noise only in the communications channel. Sometimes, the presence of only one source of noise in the diagram of Fig. 2.2 is explained by the fact that all noise sources are combined into one. In calculation of noise power in the system, this can be done. However, not simply an estimate of noise power is important, but taking account of degradation of messages by noise in the corresponding components.[1]

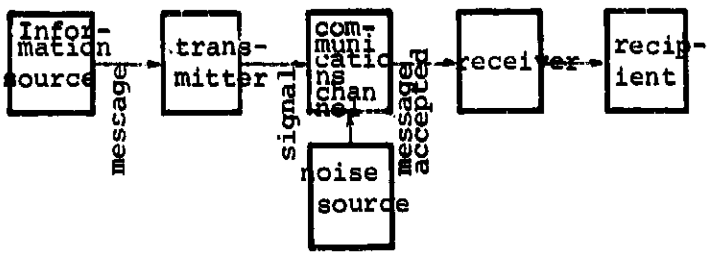


Fig. 2.2 Structural diagram of communications system according to Shannon

We turn to the structural diagram of a television system with noise sources (Fig. 2.3). The source of a message (image) is a scene, an object of observation. The carrier of information about the object observed is light, i.e., electromagnetic waves in the optical range, reflected or radiated by the object. The optical image is a macroscopic description of the electromagnetic waves. The mathematical description of an image is a function of three Cartesian coordinates, /75 time and wavelength $m(x, y, z, t, \lambda)$. Image $m(x, y, z, t, \lambda)$ gives a description of the electromagnetic waves of reflected objects, only on the part of useful information about the object. Another theoretically inherent aspect of the description of electromagnetic waves is photon noise. Photon noise is the result of

---

[1] In the structural diagram (Fig. 2.2), a transmitted signal is a coded message, not taking account of noise, and the received signal, is the sum of the transmitted signal and noise. Such use of the term "signal" is not harmonious. We will apply the term "message" to a message carrying useful information about an object in uncoded or coded form, and the term "signal," to the sum of the message and noise.

macroscopic appearance of electromagnetic radiation of a quantum nature. Therefore, the model of an optical signal reaching a television system input is the sum of two functions, generated simultaneously and theoretically indivisible: Of the optical image and photon noise; $r(x, y, z, t, \lambda) = m(x, y, z, t, \lambda) + n(x, y, z, t, \lambda)$.

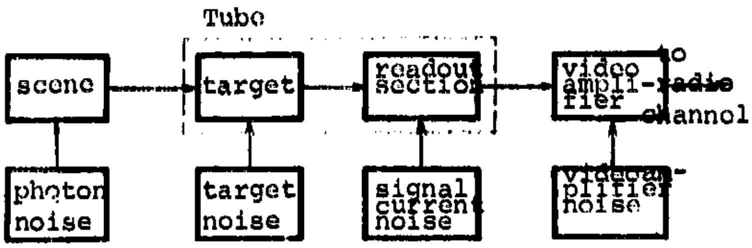


Fig. 2.3 Source of noise in a television system

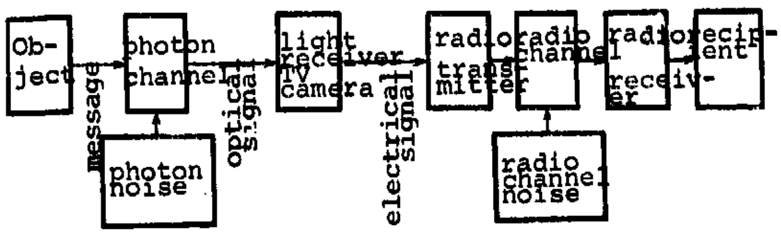


Fig. 2.4 Generalized structural diagram of television system

In the conversion process, the optical signal is distorted in the television system components by the inherent noises of these components. There is not a single component in a television system, in which conversion of a pure image (message) can be accomplished in the absence of noise. A generalized structural diagram of a television system can be constructed, which is represented in Fig. 2.4. The diagram contains two channels and two types of electromagnetic wave receivers: optical and radio range, and it reflects the obvious fact that the television transmitting camera is a component of the system, performing the function of receiver of electromagnetic radiation in the optical range, to which optimum reception theory must be extended.

The difficulty in bringing into being an optimum receiver, the concept of which is given in section 2.1, consists of difficulties in creating the storage device and resolver.

For clarity, we use a set of N unit vectors, in the form of displaced square pulses $g(k\Delta t)$, of duration Δt and unit energy (see section 1.5). Then, we present a discrete message in interval

T, in analytical form, as

$$m_i(t) = \sum_{k=1}^{N} m_{ik} g(t - k\Delta t), \quad i = 0, 1, 2, \ldots, M-1, \tag{2.13}$$

where $N = T/\Delta t$.

We will distinguish two types of messages: /76

1. Complex, the size of a set of which is determined by the quantity $M = S^N$, where N is the number of symbols in the message and S is the number of symbols in the alphabet.

   Just such a set of messages is analyzed in a statement of the measure of information.

2. The simplest messages, for which the number of possible messages is equal to the number of unit vectors: $M = N$.

   An example of the simplest one is a message, which is a square pulse, coinciding with one of N unit vectors:

$$m_i(t) = \sum_{k=1}^{N} A\delta_{ik} g(t - k\Delta t) = Ag(t - i\Delta t), \; k = 1, 2, \ldots, N, \tag{2.14}$$

   where A is the pulse amplitude and δ_{ik} is the Kroneker symbol.

Receipt of the simplest message entails the production of an amount of information equal to $\log_2 N$ binary units, in place of the quantity $N\log_2 S$ binary units, in the first case.

One possible storage device consists of a mosaic of filters matching the unit vectors.

A matched filter is an ideal pulse energy storage device. The signal-noise ratio at the output of a filter-matched pulse (2.14):

$$q^2 = \frac{2E}{S_n} = \frac{2A^2\Delta t}{S_n}, \tag{2.15}$$

where $E = A^2\Delta t$ is the stored pulse energy and S_n is the spectral density of the noise power at the filter input.

Applied to extraction of the current pulse of amplitude ΔI on a background of current I_ϕ (see Fig. 2.5), formula (2.15) is transformed to the form

$$q = \sqrt{\frac{2\Delta I^2\Delta t}{S_n}} = \sqrt{\frac{2\Delta I^2\Delta t}{2eI_\phi}} = k\sqrt{N_e}, \tag{2.16}$$

where $S_n = 2eI_\phi$ is the spectral density of the background current shot noise, N_e is the mean number of background electrons, summed over the pulse time and

$$k = \frac{\Delta I}{I_\phi}$$

is the pulse contrast.

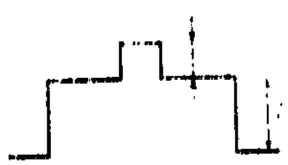


Fig. 2.5 Square current pulse on background

Formula (2.16) coincides with the previously introduced formula (1.3), and it shows that a matched filter serves as an ideal electron summator.

The complexity of a storage device increases almost linearly in the general case, with increase in number of symbols N in the message. In the partial case, when message (2.13) is a discrete function of time t and $g(t - k\Delta t)$ are time pulses, it is sufficient to use just a single matched filter. In this case, a solution can be adopted, on the basis of selection of signal records at the output of the single matched filter, at moments of time [3, p. 350] $k\Delta t$, where $k = 1, 2, \ldots, N$.

Storage of a priori information on the set of messages trans- /77
mitted is necessary for creation of the receiver resolver. This information is necessary for making a decision on selection of one message. It is evident that, for storage of M messages which differ from one another, even in one bit of data, requires a memory of capacity M bits[39]. Consequently, the optimum receiver should have a working memory on the order of M bits. The memory is called a working one, since inspection of the memorized data is necessary for making a decision in a limited time T_{res}. In order to estimate the capacity of the working memory, we consider that the number of unit vectors required for presentation of a set of M discrete messages, N always $\leq M$ [3, p. 221].

Optimum receivers for the two types of messages are distinguished by the required memory capacity M. For one type $M = S^N$ bits, and the memory increases exponentially with increase in the symbols N making up the message. The memory capacity of a digital computer, on the order of $M = 10^8$ bits, would be sufficient only for receiving messages of eight symbols in an alphabet of $S = 10$ symbols. For the second type (receipt of simplest message [formula 2.14]), a memory capacity of N bits in all is required. A storage device of N matched filters possesses such a memory.

Using a priori information stored in the memory, the resolver must carry out MN calculations of the distances between vectors

$$d_i^2 = \sum_{k=1}^{N} (r_k - m_{ik})^2, \quad i = 0, 1, 2, \ldots, M-1.$$

These calculations must be carried out in decisiontime T_{res}. If a message is complex ($M = S^W$), the volume of calculations required in time T_{res} increases exponentially with increase in number of symbols N in the message. If the calculations are carried out sequentially in time, this means an exponential growth in the calculation speed, which is inaccessible to the technology. In carrying out calculations in parallel in time, an exponential increase in number of parts in the computer is required [3, p. 350]. When the message is the simplest one ($M = N$), a total of N calculations must be carried out to make a decision:

$$\min (r_k - A)^2, \ k = 1, 2, \ldots, N.$$

Let us apply what has been said to a receiver of discrete optical images in television.

Creation of an optimum receiver of the simplest image is within the reach of television (see Fig. 1.28). Such an image, with account taken of the change from a single argument t to Cartesian coordinates (x, y), and the observation time interval T, is a two-dimensional square pulse, i.e., a square spot (see section 1.5)

$$m_i(x, y) = Ag(x - i_x\Delta x, \ y - i_y\Delta y),$$

where $i_x = 1, 2, \ldots, z$, and $i_y = 1, 2, \ldots, z$.

A spot of area $\Delta x \Delta y$ (in which $\Delta x = \Delta y$) is located on a uniformly bright background of area $L^2 = z^2\Delta x \Delta y$. /78

For simplicity, the entire movement trajectory of the spot will not be examined, but the position of the spot in a single interval of time, equal to the exposure time T_e, during which the spot is stationary, to within Δx.

The number of images in a set equals the number N of possible positions of the spot in field L^2. Selection of the image from a set means detection of the spot and measurement of its coordinates, which are accompanied by production of $\log_2 N$ bits of data.

The optimum receiver will contain N matched filters, which are photon or photoelectron storage devices, and a simple resolver, which, from N readouts of r_{ik} from the filter outlets, selects the one, in accordance with rule (2.12), which is closest to the pulse amplitude. We compare such a receiver with a known television system (see section 3.4). It is easy to note that both resolvers are identical in type of images received and functions performed. A second difference in the resolvers are identical in type of images received and functions performed. A certain difference in the resolvers is caused by substitution of the probability rule, based on the Neumann-Pearson criterion, for decision rule (2.12).

The main thing which flows from the theory of the optimum receiver is the fact that an optimum television camera should contain, not a single storage device, but a mosaic of N photon storage devices. This recommendation of the theory of the optimum receiver coincides completely with experience in building similar television systems, having the greatest light sensitivity.

Creation of an optimum receiver of the simplest image is simplified still more in the partial case, when the spot coordinates are known a priori. In this case, the set of possible messages is decreased from N to 2: There is a spot and there is not a spot. The amount of data produced is one bit. The optimim receiver for solution of this detection problem consists of a total of only one storage device (a matched filter) and a resolver, in the form of a threshold limiter.

In practice, creation of optimum receivers encounters the problem of control, not only of the external noise accompanying a message entering the receiver inlet, but control of the inherent internal noise of the receiver circuit. An effective means of control of internal noise in presence of external noise is matching the power of the two noise sources, by means of amplifying or coding the message. The message, together with the external noise, is amplified to a level, at which the power of the external noise exceeds that of the internal.[1]

Let us consider the possibility of building an optimum receiver of complex, discrete images in television.

It is well-known from experience in space television that the lower limit of acceptable definition of the television frame corresponds to a 100 line scan or $N = 10^4$ elements (symbols) per frame (see Chap. 5). With an average number of gradations per symbol $S = 10$, a discrete image with definition $N = 10^4$ elements forms a set of $M = 10^{10000}$ possible images. /79

Making a decision on selection (discrimination) of one image from such a set would require a resolver with a working memory capacity on the order of 10^{10000} bits. In this case, there is nothing left but to give up building a receiver with a resolver. The possibility remains of making a storage device for the optimum receiver, which can be called a receiver without a resolver. The television camera is just such a receiver. The purpose of a television camera is delivery of readouts $(m_{i1}, m_{i2}, \ldots, m_{iN})$ of information for subsequent semantic processing by their recipient, a man.

Therefore, two definitions of a receiver are encountered: In the broad sense of this word, a receiver with a resolver (when this

---

[1]The importance of the operations of amplification and coding an optical signal for noise control in television has been discussed in articles [40, 41].

can be realized technically) and, in the narrow sense, a receiver without a resolver, the function of which can be performed only by man.

It should be emphasized that what has been said holds true within the framework of theory, based on a statistical model of a message and on the concept of nonsemantic information. The limited nature of these concepts has already been noted in section 2.1. In life, man uses such an optimum receiver as the visual analyzer (the eyes), which, with a relatively small memory capacity (the memory capacity of the brain is estimated to be on the order of 10^{9} bit) distinguishes images very well, with a definition of over 10^4 elements. It is obvious that the visual analyzer has a very effective method of description of an image ("visual language"), with the aid of which a gigantic set of statistical images is successfully reduced to an acceptable volume of semantic images.

Modern television technology is far from such a capability. The only thing which can be done is to artificially limit the purpose of an optimum television receiver by an automatic selection (discrimination) of a limited number of images from a set S^N images, equal, for example, to N. The required memory is then reduced to N television frames, with a definition of N elements, which can be accomplished on photographic film.

2.3 Models of Continuous Messages and Their Information Characteristics

Discrete messages were examined in sections 2.1 and 2.2. The specifics of television includes receiving and transmitting continuous messages. When it is desired to explain the concept of a continuous message, as a rule, one turns to the example of optical images. An electric video signal (within a single line) at the television camera output is an illustration of a continuous signal, i.e., the sum of a continuous image and noise in electrical form. Reasoning by analogy with the statistical model of a discrete message, a statistical model of a continuous message can be constructed, in the form of a continuum (i.e., infinitely large) set of continuous functions m(t), limited by argument t and called finite [42]. Random function m(t) should be finite, in order to reflect the properties of real continuous messages, which always have a beginning and an end, i.e., $m(t) = 0$ at $t < 0$ and $t > T$. /80

Thus, the model of a continuous message is a transient random function m(t), differing from zero in finite T, i.e., a finite random function. Although such a model reflects real messages well, it is difficult to analyze mathematically, by virtue of the transience. A model, in the form of a steady random function, defined on the entire axis of the argument t, is more convenient. A steady model, like a transient one, reflects the major property of real messages, their unpredictability with zero error. It was shown in work [26] that the condition of impossibility of prediction (extrapolation) of the function as far ahead as desired, with as small an error as desired, is written in the form

$$\int_{-\infty}^{\infty} \frac{|\log S_m(f)|}{1+f^2}\, df < \infty, \tag{2.17}$$

where $S_m(f)$ is the spectral density of the power (energy spectrum) of random function $m(t)$.

From the Kolmogorov conditions of unpredictability of a signal (2.17), it follows that the spectral density of a continuous message cannot be limited, i.e., it does not equal zero on the frequency half-axis, and it cannot decrease expontentially. In fact, if $S_m(f) = 0$ at $f > f_{lim}$, integral (2.17) diverges.

In probability theory[43], the possibility has been proved of representation of a steady random function by the series

$$m(t) = \sum_{k=-\infty}^{\infty} m_k \varphi_k(t), \tag{2.18}$$

where $m_k = \int_{-\infty}^{\infty} m(t)\varphi_k(t)\,dt,\ \varphi_k(t)$

are unit vectors defined by solution of an integral equation dependent on the correlation function of process $m(t)$.[1]

Series (2.18) has a theoretical value, demonstrating the possibility of geometric representation of a steady, random function, /81
by a vector in space of an infinite number of dimensions, with unit vectors $\{\phi_k(t)\}$. However, by virtue of the difficulty of definition of these unit vectors in the general case and the complexity of their form for partial cases [43], series (2.18) has not become widespread in engineering practice up to this time. It is possible that precisely this difficulty should explain the fact that another, so-called singular model of a continuous message, which is simpler, is more widely used in communications theory up to the present time, since it is constructed on the basis of a truncated Kotel'nikov series. Let us examine this model.

The idea of replacement of analysis of transmission of a continuous function through a communications channel by transmission of a sequence of discrete values of it is contained in works [36] and [18]. The approximate nature and artificiality of such a replace-

---

[1]The integral equation was introduced in work [43, p. 118]. It is not introduced here, since it is not used subsequently.

ment has been noted [18, p. 15]. This idea can be considered to be a transfer to communications theory of the mathematical problem of tabulation of continuous functions, i.e., of the approximate representation of the latter by tables of numbers. This idea received a significantly more complete basis in the work of Kotel'nikov in 1933 [44]. In accordance with the Kotel'nikov theorem, if function m(t) has a limited spectrum, i.e., its Fourier transform equals zero at frequencies above limit F, it has an orthogonal representation in the form of the series

$$m(t)=\sum_{k=-\infty}^{\infty} m_k \psi(t-k\Delta t), \tag{2.19}$$

where

$$m_k=\int_{-\infty}^{\infty} m(t)\psi(t-k\Delta t)\,dt=m(k\Delta t)\sqrt{\Delta t},$$

$$\psi(t-k\Delta t)=\frac{\sin\frac{\pi}{\Delta t}(t-k\Delta t)}{\frac{\pi}{\Delta t}(t-k\Delta t)}\,\frac{1}{\sqrt{\Delta t}},\quad \Delta t=\frac{1}{2F}.$$

The simple form of unit vector $\psi(k\Delta t)$ and the simple method of calculation of coefficients m_k, which are proportional to the instantaneous values of $m(k\Delta t)$ of the function, make it convenient to use series (2.19) in communications technology. The requirement for transmission of an infinitely large number of readouts $m(k\Delta t)$ of the function, which differs from zero along the entire axis of argument $t \in [-\infty, \infty]$, causes an inconvenience. Real messages differ from zero only in interval T. Clearly, there have to be readouts (symbols, elements) in this interval,

$$N=\frac{T}{\Delta t}=2TF. \tag{2.20}$$

In order to take account of this circumstance, it is considered that all readouts outside of interval T equal zero: $m_k = 0$ at $k < -N/2$ and $k > N/2$. The Kotel'nikov series then de- /82
generates into the sum

$$m(t)=\sum_{k=-\frac{N}{2}}^{\frac{N}{2}} m_k \psi(t-k\Delta t)=\sum_{i=1}^{N} m_i \psi(t-i\Delta t). \tag{2.21}$$

Sum (2.21) has a geometric representation, is an N-dimensional vector in the space of unit vector $\psi(t-k\Delta t)$. Consequently, the continuum of continuous functions $m(t)$ can be replaced by a set of vectors $\{\vec{m}\}$, of finite dimensions.[1]

---

[1]The term "set of functions with limited duration" is used in work [6, p. 295]. The incorrectness of this term is explained in work [42, p. 174].

It is easy to see that the model of a continuous message, in the form of set (2.21), does not satisfy Kolmogorov condition (2.17), i.e., it is singular. The functions with a limited spectrum belong to a special class, the so-called integral analytic functions [42]. The analytical nature of the function makes possible its extrapolation with zero error. Consequently, the singular model does not reflect the major characteristic of real messages. However, despite this incorrectness of the singular model of a continuous message, it is simple and, therefore, facilitates widespread distribution in communications theory. In particular, this model is the basis of information theory for continuous messages, reported in the well-known work of Shannon [6]. In sum (2.21), coefficients m_k are considered as unidimensional random values, having a continuous probability distribution $P(m_k)$, at

$$m_k \in [-\infty, \infty].$$

It is evident that uniform distribution of probabilities (all values of m_k in the range $[-\infty, \infty]$ are equally probable) has an infinite entropy value. However, for a normal (Gaussian) probability distribution

$$P(m_k) = \frac{1}{\sqrt{2\pi \overline{m_k^2}}} e^{-\frac{m_k^2}{2\overline{m_k^2}}}, \quad m_k \in [-\infty, \infty],$$

where $\overline{m_k^2}$ is the dispersion, the entropy in a finite symbol:

$$H_1(m_k) = \frac{1}{2} \log_2 2\pi e \overline{m_k^2}.$$

Then, the entropy of the singular model of a continuous message is finite and, independently of coefficients m_k:

$$H(m) = \frac{1}{2} \sum_{k=1}^{N} \log_2 2\pi e \overline{m_k^2}. \tag{2.22}$$

We will consider that the dispersion of all readouts equals: /83

$$\overline{m_k^2} = \sigma_k^2 \tag{2.23}$$

The expression for the entropy of a continuous message, presented in work [6, p.298], flows from formula (2.22), under condition (2.23): $H(m) = TF\log_2 2\pi e\sigma^2$ bits or, in the unit time,

$$H'(m) = F\log_2 2\pi e\sigma^2 \text{ bit/sec.} \tag{2.24}$$

The entropy of the singular model of a white, Gaussian noise, with band frequency F and average power P_n [6, p. 300] $H'(n) = F\log_2 2\pi e P_n$. A continuous signal passes along the communications channel, which is the sum of a continuous message and noise: $r(t) = m(t) + n(t)$.

The information characteristics of a communications channel with restricted frequency band F is the throughput capability (capacity)

$$C = \max[H'(m) - H'_r(m)] \text{ bit/sec.}$$

The Shannon formula for calculation of throughput capacity in white noise:

$$C = F\log_2\left[1 + \frac{P_m}{P_n}\right] \text{ bit/sec,} \tag{2.25}$$

where P_m is the average power of the message, P_n is the average power of the white noise.

We note that, by formula (2.25), even under the conditions $0<P_m<P_n$, the throughput capability of a channel can increase, although slowly, with increase in frequency band F.

For a nonwhite Gaussian noise, the throughput capability is calculated by another formula of Shannon [6, p. 454]:

$$C = \int_0^F \log_2\left[1 + \frac{S_m(f)}{S_n(f)}\right] df, \tag{2.26}$$

where $S_m(f)$, $S_n(f)$ are the spectral densities of the power of the message $m(t)$ and noise $n(t)$.

Formulas (2.25) and (2.26), for calculation of throughput capability, are widely known, and they are introduced in all popular presentations of information theory. Another information quantity introduced by Shannon, for the characteristics of the source of continuous messages, the rate R of creation of a message with the root mean fidelity criterion of reproduction of the message [6], is less well-known. When a set of messages is a singular white noise, with average power Q, the quantity [6, p. 321] $R = \min[H(m) - H_r(m)] = H(m) - \max H_r(m)$.

However, the maximum entropy $H_r(m)$ is reached, when the deviation of function $r(t)$ from the initial message $m(t)$ is white noise. /84
Therefore,

$$R = H(m) - H(n) = F\log_2\frac{Q}{P_n}, \tag{2.27}$$

where P_n is the permissible root mean deviation of the reproduced message from the original one, equal to the white noise power.

According to formula (2.27), the rate $R>0$ only under the condition $Q>P_n$.

We emphasize once more that the formulas introduced (2.24), (2.25), (2.26) and (2.27) were obtained for partially limited (singular) models of a message and a channel.

In the works of Viner [7] and Kolmogorov [5], a model of a continuous message was used, in the form of a stationary, random function.

The entropy of the random function is infinite. Therefore, the principal information concept allowing generalization to continuous messages is not directly the concept of entropy, but the concept of amount of information in the observed (measured) random function, relative to another random function [7, p. 78]. By calculating the amount of information contained in the sum of a continuous message m and noise n relative to the message only, Viner gives the following formula [7, p. 149]:

$$I(m;\, n, m) = \int_{-\infty}^{\infty} \log_2 \left[1 + \frac{S_m(f)}{S_n(f)}\right] df, \text{ bit/sec.} \qquad (2.28)$$

Formulas (2.28) and (2.26) differ only in the integration limits. The spectral densities of a message $S_m(f)$ and noise $S_n(f)$ in (2.28) are not limited by frequency band; therefore, the integration is done along the entire frequency axis. The spectral densities satisfy condition [45]

$$\lim_{f\to\infty} \frac{S_m(f)}{S_n(f)} = 0.$$

Therefore, improper integral (2.28) converges. It is clear from formula (2.28) that even those high-frequency sections of message spectrum, at which $S_m(f) < S_n(f)$, make a positive contribution to the amount of information in the message. The coincidence of formulas (2.26) and (2.28) shows that the latter concerned finding the throughput capability C and not the rate of message creation R.

The method of calculation of R is given in the work of Kolmogorov [5], where the quantity R is called the ε entropy. Although the entropy of a continuous message (of a random vector of infinite dimensions) is infinite, by assigning an error in observation of the message greater than zero, a finite value of the ε entropy of R, obtained as a result of observation, can be determined. In partial cases, the method of calculation of the ε entropy gives simple formulas, including formula (2.27). We introduce these formulas. We begin with the formula for calculation of the ε entropy /85 applicable to a model of a discrete message, in form of an N-dimensional random vector

$$\vec{m} = (m_1, m_2, \ldots, m_N).$$

Formulation of the problem in the work of Kolmogorov [5] is similar. In the observation process, let $\vec{m}$ be approximated by vector $\vec{\beta}$, with a fixed root mean error

$$\varepsilon = 0 \cdot |\vec{m} - \vec{\beta}|^2 \leq \varepsilon^2.$$

The error approximation factor

$$\vec{\Delta} = \vec{m} - \vec{\beta}$$

The spaces of vector $\vec{m}$ and $\vec{\beta}$ coincide, i.e., it is known a priori that the unit vectors of vectors $\{\phi_k(t)\}$ are identical. Coordinates m_k of vector m are mutually independent, and they have a continuous normal probability distribution. Vectors $\vec{m}$ and $\vec{\Delta}$ also are mutually independent.

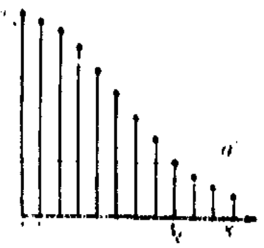


Fig. 2.6 Calculation of ε entropy of a discrete message

The entropy of vector $\vec{m}$ at zero error $\varepsilon = 0$ is determined by formula (2.22). We calculate the ε entropy, with a fixed error $\varepsilon > 0$. We consider that, in the general case, the values of dispersion $\overline{m_k^2}$ are nonuniform, i.e., condition (2.23) is not satisfied. By means of simple renumbering of subscripts k, the dispersion can be arranged in decreasing order of value (see Fig. 2.6). Then, with a fixed $\varepsilon > 0$, the quantity θ^2 is introduced, which determines the level of limitation from the equation [5, p. 87]

$$\varepsilon^2 = \sum \min(\theta^2, m_k^2). \qquad (2.29)$$

Solution of equation (2.29) requires comparison of the dispersion $\overline{m_k^2}$ with the limiting condition θ^2. A case is possible, when $\overline{m_k^2} > \theta^2$ at all

$$k \in [1, N].$$

However, if the error in approximation is not too small, the case depicted in Fig. 2.6 is possible. The range of subscripts k is divided into two sections, depending on the value of θ^2: $\overline{m_k^2} \geq \theta^2$ at $k = 1, 2, \ldots, N_\varepsilon$ and $\overline{m_k^2} \geq \theta^2$ at $k = N_\varepsilon, N_\varepsilon + 1, \ldots, N$. Equation (2.29) can then be rewritten in the form

$$\varepsilon^2 = \theta^2 N_\varepsilon + \sum_{k=N_\varepsilon+1}^{N} m_k^2 \qquad (2.30)$$

Equation (2.30) shows that, owing to not too small an error in approximation ($\varepsilon > 0$), it will be impossible to observe part of the coordinate m_k at $k > N_\varepsilon$. Therefore, approximating vector $\vec{\beta} = (\beta_1, \beta_2, \ldots, \beta_N)$ should be selected, so that [5, p. 88]

$$\beta_k = \begin{cases} m_k - \lambda_k & \text{at } k = 1, 2, \ldots, N_\varepsilon, \\ 0 & \text{at } k = N_\varepsilon + 1, \ldots, N. \end{cases}$$

This means degeneration of approximating vector $\vec{\beta}$: It turns out to be not N-dimensional, but only N_ε-dimensional. It is evident that the following relationships hold true: /86

$$\lambda_k^2 = \begin{cases} \theta^2 & \text{at } k = 1, 2, \ldots, N_\varepsilon, \\ m_k^2 & \text{at } k = N_\varepsilon + 1, \ldots, N, \end{cases}$$

$$\beta_k^2 = \begin{cases} m_k^2 - \theta^2 & \text{at } k = 1, 2, \ldots, N_\varepsilon, \\ 0 & \text{at } k = N_\varepsilon + 1, \ldots, N. \end{cases}$$

The ε entropy R is determined by the formula [5, p. 87]

$$R = \frac{1}{2} \sum_{k=1}^{N_\varepsilon} \log_2 \frac{m_k^2}{\theta^2}, \text{ bits.} \qquad (2.31)$$

Calculation of ε entropy for a vector having an infinite number of dimensions differs in no way from the case of a finite-dimensional one; moreover, the circumstance that a vector with an infinite number of dimensions will always degenerate, while this is not obligatory for a vector of a finite number of dimensions. Based on this, we introduce the ε entropy of the equilibrium random function m(t) by its power density $S_m(f)$. The limitation level θ is determined from the equation

$$\varepsilon^2 = \int_0^\infty \min[\theta^2, S_m(f)]\,df. \qquad (2.32)$$

By means of θ, the ε entropy value is found by the formula (compare with formula [2.41])

$$R = \frac{1}{2} \int \log_2 \frac{S_m(f)}{\theta^2}\,df, \text{ bit/sec,} \qquad (2.33)$$

where $S_m(f) > \theta^2$.

In order to explain formulas (2.32) and (2.33), we turn to the frequency-unlimited, monotonically decreasing spectral density $S_m(f)$

(see Fig. 2.7). It can be noted that the limitation level θ^2 determines the finite frequency band F_ε to be such that $S_m(f) \geq \theta^2$ at $f \leq F_\varepsilon$, $S_m(f) < \theta^2$ at $f > F_\varepsilon$, where F_ε is found from equation

$$S_m(F_\varepsilon) = \theta^2. \tag{2.34}$$

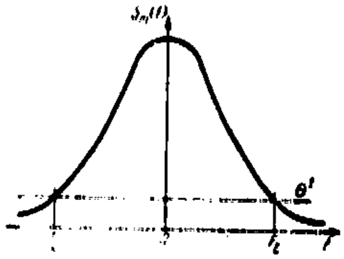


Fig. 2.7 Calculation of ε entropy of a continuous message

Taking equation (2.34) into consideration, we rewrite calculation formulas (2.32) and (2.33) in the form

$$R = \int_0^{F_\varepsilon} \log_2 \frac{S_m(f)}{\theta^2}\, df \text{ bit/sec}, \tag{2.35}$$

where θ^2 is found from the equation

$$\frac{1}{2}\varepsilon^2 = \theta^2 F_\varepsilon + \int_{F_\varepsilon}^{\infty} S_m(f)\, df. \tag{2.36}$$

It is evident from (2.35) and (2.36) that, if the root mean error $\varepsilon = 0$, the frequency band $F_\varepsilon = \infty$ and ε entropy $R = \infty$. Assignment of not too small a root mean error $\varepsilon > 0$ is accompanied by loss of an infinitely large amount of information contained in the high-frequency part of the spectrum $S_m(f)$. From the energy point of view, rejection of this part of the spectrum $S_m(f)$ means loss of only a small fraction of the power in all: /87

$$\eta = \frac{P_{m\,\text{sp}}}{P_m} = \frac{\int_{F_\varepsilon}^{\infty} S_m(f)\, df}{\int_0^{\infty} S_m(f)\, df} < 1.$$

Quantity of information R remains accessible to observation in the limited frequency band F_ε.

Formula (2.35) changes into formula (2.27), upon incorporation of singularity into the spectral density $S_m(f)$. We assume that

$$S_m(f) = \begin{cases} S_m & \text{at } f \leq F_\varepsilon, \\ 0 & \text{at } f > F_\varepsilon. \end{cases} \tag{2.37}$$

Then, message power $Q = S_m 2F_\varepsilon$. We have $Q^2 = \varepsilon^2/2F_\varepsilon$ from (2.36). By substituting the values of Q and θ^2 in (2.35), taking (2.37) into consideration, we obtain $R = F_\varepsilon \log_2 Q/\varepsilon^2$. This formula coincides with formula (2.27) at $\varepsilon^2 = P_n$.

Obtaining the formula of Shannon from the more general formula (2.35) involves a fundamental innovation, which consists of the fact that it now is evident, why and within what limits (with not too small ε) the formula of Shannon can be applied to processes with an unlimited spectrum, and these are of more and more urgent interest to us in the theory of message transmission [5, p. 93].

The circumstance mentioned, beside theoretical importance, is of great practical importance. It consists of the fact that the use of formulas (2.25) and (2.27) in engineering calculations strikes the indeterminacy in finding the frequency band F applicable to real objects. It is known that all real linear filters satisfy the Paley-Viner condition (1.15) and are not frequency-limited. A process with a limited spectrum cannot be formulated by means of them. A pulse which can be formed in radio engineering always has a limited duration and an unlimited spectrum (Fourier transform).

Determination of a finite frequency band F_ε for a continuous message with spectral density $S_m(f)$, which is not frequency-limited, contained in work [5], provided a way out of this difficult position. /88

2.4 Specifics of Theory of Reception of Continuous Messages

It was noted in section 2.1 that one of the initial points in the theory of optimum reception of discrete messages is the assumption of coincidence of the functional space of the signal at the receiver outlet with the a priori known space of the incoming message. This assumption permits an optimum receiver, containing filters, the number of which and pulse characteristics of which are known (N filters matching the unit vectors), to be constructed, on the basis of a priori knowledge of the set of N unit vectors $\{\phi_k(t)\}$ of the incoming message.

The method of calculation of the ε entropy of the continuous message, stated in section 2.3, also assumes a priori knowledge of the message unit vector and matching of the spaces of the output signal and the incoming message.

For a statistical model of a continuous message, the question of a priori knowledge of the unit vectors is determined by series expansion (2.18). Finding the unit vector requires a priori knowledge of the correlation function of a continuous message and solution of the corresponding integral equation [43]. The correlation function of an optical image received is not known a priori in television (we have complicated subjects in mind). Nevertheless, a receiver of optical images under such conditions must be planned. Even if the correlation function were to be known a priori and, having solved the integral equation, the unit vectors were to be found successfully, their number would be infinite (as could be expected), constructing a receiver with an infinite number of filters would not appear to be possible. Therefore, the specifics of optimum reception of a continuous message must be examined, due to the fact that the correlation function is not known a priori and the output signal space cannot be matched with the unknown message space. We carry out such an examination, applicable to an optical image, keeping in mind the singularities of television, which does not disrupt the generality of the conclusions. Let a continuous signal enter the receiver inlet: the former is the sum of two random functions: The continuous message (optical image) $\xi(t)$, which is an analytical record of an object being studied, and of white Gaussian noise $n_\infty(t)$: $\{\xi(t) + n_\infty(t)\}$.

Random process $\xi(t)$ is determined in interval T, in which it has a finite energy E_ξ; the correlation function of the process is not known a priori. A flat optical image is a function of four arguments $\xi(x, y, t, \lambda)$, but for purposes of simplification of the writing of the mathematical expressions, we use one argument t. /89

Considering the a priori lack of knowledge of the message unit vector $\xi(t)$, we arbitrarily select the functional space of the output signal. As a working hypothesis, we use the space defined by $N = T/\Delta t$ with angular pulse unit vectors $g(k\Delta t)$(see section 1.5). Message $\xi(t)$ is represented in the space selected with distortions. This representation is discrete and, consequently, it can be represented geometrically by the random, N-dimensional vector:

$$\vec{m}_i = (m_{i1}, m_{i2}, \ldots, m_{iN}), \quad i = 0, 1, 2, \ldots, M-1,$$

$$m_{ik} = \int_{-\infty}^{\infty} \xi(t) g(t - k\Delta t) dt = \sqrt{\Delta t} \frac{1}{\Delta t} \int_{(k-1)\Delta t}^{k\Delta t} \xi(t) dt.$$

The analytical form of the discrete representation of message $\xi(t)$ is a set of functions

$$m_i(t) = \sum_{k=1}^{N} m_{ik} g(t - k\Delta t), \quad i = 0, 1,$$

2, . . ., M - 1. It is evident that

$$\sum_{k=1}^{N} m_{ik}^2 = \sum_{k=1}^{N} \Delta t \left[\frac{1}{\Delta t} \int_{(k-1)\Delta t}^{k\Delta t} \xi(t) dt \right]^2 < E_\xi .$$

The discrete representation $m_i(t)$ of continuous message $\xi(t)$ contains, although with distortions, useful information on the object being studied. We set up the problem of optimum reception of discrete representation $m_i(t)$ on a background of white noise $n_\infty(t)$: $r_\infty(t) = m_i(t) + n_\infty(t)$.

Such an optimum receiver is known, and it has already been described in sections 2.1 and 2.2. We repeat that the receiver contains a mosaic of N photon storage devices (matched filters).

The storage devices (filters) have rectangular (square) pulse characteristics, differing only by the shift $h_k(t) = cg(t_0 - k\Delta t)$, where c and t_0 are constant and identical transmission functions;

$$h(f) = \frac{\sin \pi \Delta t f}{\pi \Delta t f}. \qquad (2.38)$$

The signal at the receiver output is the reality of the random vector

$$\vec{r}_i = \vec{m}_i + \vec{n},$$

where

$$\vec{n} = (n_1, n_2, \ldots, n_N),\ n_k = \int_{-\infty}^{\infty} n_w(t) g(t - k\Delta t)\, dt.$$

It was noted earlier that, in the receiving process, the white noise vector "degenerates" changing from an infinite number of dimensions to N-dimensional. The presence of noise vector $\vec{n}$ interferes with precise measurement of the coefficients m_{ik} from readings of $r_{ik} = m_{ik} + n_k$. /90

We find an estimate of the amount of information R at the outlet of such a receiver. Useful information is contained in the measurement of coefficients m_{ik} from readings of r_{ik} at the output of the matched filters. Measurement of coefficient m_{ik} is a well-known problem of estimation of the amplitude of a rectangular pulse on a background of noise $\vec{n}$. The signal-noise ratio at the output of the k-th matched filter is

$$q_k = \frac{2E_k}{S_n} = \frac{2\overline{m^2_{ik}}}{S_n},$$

where $E_k = \overline{m^2_{ik}}$ is the stored energy of the k-th coefficient (averaging is carried out over all subscripts)

$$i \in [0, M-1]),\ S_n$$

is the spectral density of the white noise power.

Considering the matched filters as a mosaic of photon storage devices, we take into account that the quantity Q_k is determined by the number N_{ek} of stored photons (see formula [2.16], at a contrast which equals unity);

$$q_k = \sqrt{N_{ek}}. \qquad (2.39)$$

For measurement of values of m_{ik}, the signal-noise ratio Q_k must be above the threshold Q_{thr}. Accumulation of one photon cannot guarantee a reading; therefore, it is evident from (2.39) that the threshold signal-noise ratio Q_{thr} is greater than one.

Generally speaking, coefficients m_{ik} can assume values in a continuous set. However, because of the presence of noise, the results of measurement of m_{ik} from the r_{ik} readings are quantized values $\hat{m}_{ik}$, belonging to a certain output alphabet:

$$\hat{m}_{ik} \in \{m_1, m_2, \ldots, m_S\}$$

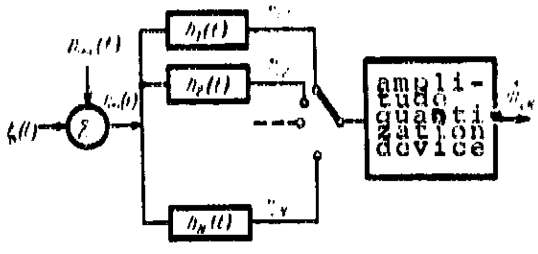


Fig. 2.8 Sequential processing of readings, by means of amplitude quantization device

Sequential processing of readings r_{ik}, by means of an amplitude quantization device, is shown in Fig. 2.8. The quantization device output alphabet contains S_k discrete amplitude values (gradations). The number of gradations

$$S_k = \frac{q_k}{q_{\text{thr}}} = \sqrt{\frac{2E_k}{S_n q^2_{\text{thr}}}} = \sqrt{\frac{2m^2_{ik}}{S_n q^2_{\text{thr}}}}$$

Consequently, the amount of information received by measurement of one coefficient m_{ik} equals $\log_2 S_k = \log_2 q_k/q_{\text{thr}}$. Neighboring m_{ik} readings at the matched filter output are distant from each other by interval Δt. Such readings are orthogonal, i.e., independent. By virtue of the independence of the readings, we obtained the desired amount of information at the output by simple summing:

$$R = \frac{1}{2}\sum_{k=1}^{N} \log_2 \frac{m^2_{ik}}{\frac{1}{2} q^2_{\text{thr}} S_n}, \text{ bits.} \tag{2.40}$$

Formula (2.40), obtained by using the signal-noise ratio at the matching filter outlet, coincides with formula (2.31), for calculation of the ε entropy, if the following equality holds true /91

$$\theta^2 = \frac{1}{2} q^2_{\text{thr}} S_n. \tag{2.41}$$

Equality (2.41) physically is completely understandable, since the threshold level θ^2, determined by the approximation error, is determined in the case being considered by the dispersion of noise, with allowance for the threshold signal-noise ratio $q_{\text{thr}} > 1$.

The receiver being considered, which is optimum for discrete image $m_i(t)$ of continuous message $\xi(t)$, is not the optimum for the message itself $\xi(t)$, by virtue of the arbitrary selection of the shape of unit vectors $g(k\Delta t)$ and the number of them N. Within the framework of the shapes of unit vectors selected in accordance with a small amount of a priori information, we improve the optimum nature of the receiver, by means of increasing the number N of unit vectors, to values guaranteeing the greatest amount of information received R. For this, the dependence of amount of information (2.40) on number of storage devices N, is analyzed.

The initial section of the R vs. N curve is obvious: at N = 0, the quantity R = 0 and, with increase in number of readings N, the amount of information R increases. The question consists of determining whether R increases monotonically to saturation with increase in N or has a maximum. We prove that R vs. N has a maximum, and we find it.

Initially, let us give a simple, intuitive explanation. With increase in $N = T/\Delta t$, the linear dimension Δt of the photon storage device decreases, i.e., $\Delta t \to 0$ as $N \to \infty$. If the finite energy E_ε of a message is taken into consideration, i.e., there is a finite number of photons entering the receiver, a decrease in the size Δt of the storage device should cause a decrease in number of photons which can be stored. While still at finite values, the number of storage devices N approaches the state, when a total of only one photon reaches one storage device. The stored image in this limiting case will be a noise picture (R = 0). This fact is well-known in optics [46, p. 148]. Consequently, there should exist a maximum R as $N \to \infty$. We proceed to formalization of this relation. /92

We consider that, at N = const, the signal-noise ratio changes from reading to reading, in the range $0 > q_k > q_S$, where k = 1, 2, . . . N.

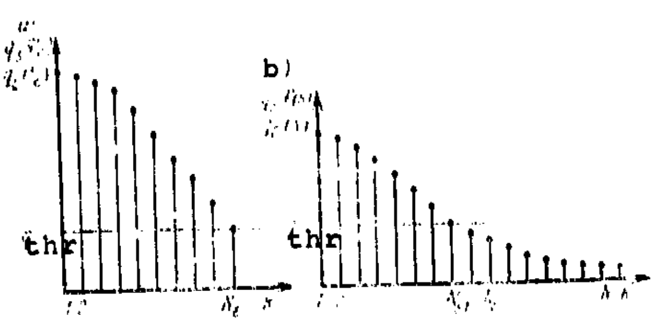


Fig. 2.9 Calculation of amount of information

We number the readings by subscript k, in order of decrease in the signal-noise ratio, and we introduce the discrete, monotonically decreasing function $\Phi(k)$, to take account of this drop (Fig. 2.9):

$$q_k = q_S \Phi(k), \quad 0 < \Phi(k) \leq 1 \qquad (2.42)$$

Substituting (2.42) in formula (2.40), we obtain

$$R = \sum_{k=1}^{N} \log_2 \frac{q_S}{q_{thr}} \Phi(k). \qquad (2.43)$$

As $N \to \infty$ and $\Delta t \to 0$, the number of photons summed by the storage device at rate Δt decreases. This causes a decrease in the signal-noise ratio: $q_S(N) \to 0$ as $N \to \infty$.

Therefore, with increase in N, we always reach number of measurements $N = N_\varepsilon$, for which the following equation will hold true

$$q_S(N_\varepsilon)\Phi(N_\varepsilon) = q_{thr} \qquad (2.44)$$

Further increase in $N > N_\varepsilon$ will cause displacement of intersection point N_ε of curve $q_S(N)\Phi(k)$ with the threshold q_{thr}, in the direction of lower subscripts, because of the drop in value of $q_S(N)$, as is shown in Fig. 2.9: $q_s(N)\Phi(N_{\varepsilon 1}) = q_{thr}$, $N_{\varepsilon 1} \leq N_\varepsilon$.

At the outlet of a receiver containing $N > N_\varepsilon$ storage devices, in accordance with (2.43), the amount of information

$$R = \sum_{k=1}^{N_{\varepsilon 1}} \log_2 \frac{q_s(N)}{q_{thr}} \Phi(k) + \sum_{k=N_{\varepsilon 1}}^{N} \log_2 \frac{q_s(N)}{q_{thr}} \Phi(k) \qquad (2.45)$$

Readings m_{ik} with subscripts $k > N_{\varepsilon 1}$ have a signal-noise ratio below the threshold. In a manner of speaking, these readings are "drowned" in noise, and they give zero information of the object. Therefore, the sum on the right in expression (2.45) equals zero, i.e., /93

$$R = \sum_{k=1}^{N_{\varepsilon 1}} \log_2 \frac{q_s(N)}{q_{thr}} \Phi(k), \text{ bits}, \qquad (2.46)$$

its, where $N_{\varepsilon 1} \leq N_\varepsilon$.

Formula (2.46) shows the increase in R with increase in N to N_ε and the subsequent drop with increase in $N > N_\varepsilon$, because of loss of readings m_{ik} with subscripts

$$k \in [N_\varepsilon, N]$$

in the noise. This proves the existence of a maximum R, with some optimum number of storage devices $N = N_{opt}$:

$$\max R = \sum_{k=1}^{N_{opt}} \log_2 \frac{q_s(N_{opt})}{q_{thr}} \Phi(k), \text{ bits}. \qquad (2.47)$$

The optimum number of storage devices in the receiver N_{opt} coincides, in the first approximation, with N_ε ($N_{opt} \sim N_\varepsilon$), i.e., there is a solution of equation (2.44).

What has been said permits formulation of a more general position (theorem) [39]: Optimum reception of continuous message $\xi(t)$, with finite energy E_ξ and an unknown correlation function, on a background of white noise, provides for extraction of the maximum amount of information (2.47) by a finite number N_{opt} storage devices. The maximum information of object being studied $\xi(t)$ is contained in its quantized representation, which is represented by N_{opt}-dimensional vector

$$\hat{m}_i = (\hat{m}_{i1}, \hat{m}_{i2}, \ldots, \hat{m}_{iN_{opt}})$$

or the sum

$$\hat{m}_i(t) = \sum_{k=1}^{N_{opt}} m_{ik} g(t - k\Delta t), \qquad (2.48)$$

where i = 0, 1, 2, . . ., M - 1.

Quantized representation $\hat{m}_i(t)$ should enter the resolver of the receiver. However, there are great difficulties in creating it for continuous messages. The first and perhaps principal difficulty consists of the requirement of extremely high memory capacity, on the order of (see section 2.2) $M = 2^{\max R}$ bits.

Therefore, there is nothing else to do but to plan the optimum receiver of continuous optical images without a resolver, narrowing the purpose of the receiver to delivery of a quantized representation $\hat{m}_i(t)$ of the object to the visual analyzer. The human brain is capable of performing the function of resolver. It is evident that, assuming the absence of noise, quantized representation (2.48) /94 should accurately represent continuous message $\xi(t)$. Let us test this. We substitute with the quantized values of coefficients in sum (2.48)

$$\hat{m}_{ik} = \frac{m_{ik}}{\theta} = \frac{\sqrt{\Delta t}}{\theta}\cdot\frac{1}{\Delta t}\int\limits_{(k-1)\Delta t}^{k\Delta t}\xi(t)\,dt,$$

where

$$\theta = \sqrt{\frac{1}{2}\,q_{\text{thr}}^2 S_n}$$

is the spacing of the quantized noise amplitude.

After substitutions, we obtain

$$\hat{m}_i(t) = \sum_{k=1}^{N_{\text{opt}}}\frac{g(t-k\Delta t)\sqrt{\Delta t}}{\theta}\,\frac{1}{\Delta t}\int\limits_{(k-1)\Delta t}^{k\Delta t}\xi(t)\,dt. \qquad (2.49)$$

We find the limit of sum (2.49) in the hypothetical case of a decrease in spectral density of the white noise power, when the condition $S_n \to 0$ is satisfied, so that $\theta = \text{const}\,\Delta t$. In this case

$$\lim_{\Delta t\to 0}\frac{g(t-k\Delta t)\sqrt{\Delta t}}{\theta} = \text{const}\,\delta(t-t_k),$$

where $\delta(t)$ is the Dirac function, and the current discrete coordinate $k\Delta t$ has changed into continuous t_k.

It follows from equation (2.44) that $N_{\text{opt}} \to \infty$ as $S_n \to 0$ (i.e., $q_{\max} \to \infty$).

Then, the limit of sum (2.49)

$$\lim_{S_n\to 0}\hat{m}_i(t) = \text{const}\int\limits_0^{\infty}\xi(t_k)\,\delta(t-t_k)\,dt_k = \text{const}\,\xi(t).$$

As should have been expected, an infinite increase in number N_{opt} of receiver storage devices permits continuous message $\xi(t)$ to be precisely reproduced, only in the hypothetical case of complete elimination of noise. In real cases of the presence of noise, construction of only discrete optimum receivers of continuous messages is possible; they give only quantized (digital) representation (2.48) at the outlet.

The general case formulated above, of representation of a continuous message on a background of white noise by an optimum receiver, in form of N_{opt}-dimensional vector (2.48), concerns solution of a key problem in communications theory, which consists of finding a method of replacing all signals by vectors of finite dimensions [3, p. 298]. We have in mind all signals, including continuous finite functions. An approximate representation of a finite, determinate function by a vector of a finite number of dimensions usually is sought, by the criterion of smallness of energy losses [3, p. 314]. N_{opt}-dimensional vector (2.48) provides a representation of a random, continuous message, on a background of white noise, by the criterion of the maximum extractable information. The number N_{opt} characterizes the maximum possible number of measurements (readings) of a continuous message which can be made, /95 with allowance for the effect of noise. Efforts to increase the number of measurements $N > N_{opt}$ only decreases the amount of extractable information. This representation permits an answer to the question of how continuous messages differ from discrete ones. Let a message be discrete and represented by a N_g-dimensional vector. The optimum reception of the discrete message is characterized by the possibility of changing from conditions of strongly distorted reception $N_g > N_{opt}$ (degeneration of the message vector) to a condition of practically undistorted reception $N_g \leq N_{opt}$, by increase in the signal-noise ratio. If the number of optimum readings N_{opt} is greater than the dimensionality of vector N_g (the number of degrees of freedom of the message), information will be contained at the receiver outlet, from which a conclusion can be drawn as to the discrete nature of the message. In distinction from discrete reception of a continuous message, which can be represented by a vector of an infinite number of dimensions, it always takes place, under conditions of "degeneration" of the dimensionality of the vector (i.e., $N_{opt} < \infty$).

However, representation of a continuous message is theoretically possible, by a vector of a finite number of dimensions, the dimensionality of which equals the number N_ϕ quanta (photons) contained in the light flux accumulated by the receiver. In optimum reception with any N_{opt}, "degeneration" of the N_ϕ-dimensional vector will always take place, since the number of photons in one measurement (in one storage device) should be greater than one: $N_\phi / N_{opt} > q^2 p_{thr} > 1$.

Replacement of an N_ϕ-dimensional vector by a continuous function goes unnoticed by an optimum receiver, because of the limiting effect of noise.

Bringing into being the optimum receiver discussed in this section runs into difficulties. First of all, it is difficult to build a mosaic of storage devices (matching filters) having rectangular pulses and amplitude-frequency characteristic (2.38). In television, the storage devices have amplitude-frequency characteristics of a given shape, which are approximated well by the function

$$K(f) = \frac{1}{1 + \left(\frac{f}{F_{0.5}}\right)^{a}}, \qquad (2.50)$$

where F_{05} is the width of the curve at the 0.5 level, i.e., $K(F_{0.5}) = 0.5$, and a is a constant.

Another difficulty is finding the optimum number N_{opt} of storage devices. Equation (2.44) and formula (2.47) give a posteriori estimates of N_{opt} and R. This means that a number of storage device mosaics, with different numbers of storage devices, must be built and N_{opt} must be found a posteriori from max R. An a priori estimate of the optimum number of storage devices is desirable, even though approximate.

We find a priori upper estimates of N_{opt} and max R for the case, when the amplitude-frequency characteristic of the storage devices K(f) is known a priori, for example (2.50). For this, we resort to formula (2.47), and we introduce a generalized frequency: $f_k = k/2T$ /96
$\Delta f_k = \Delta k/2T$, where $\Delta k = 1$.

We give an upper estimate of sum (2.47), by means of the integral

$$\sum_{k=1}^{N_{opt}} \log_2 \frac{q_S}{q_{thr}} \Phi(k) \Delta k < 2T \int_0^{F_S} \log_2 \frac{q_S}{q_{thr}} K(f)\, df, \qquad (2.51)$$

where F_S is the solution of the equation

$$q_S K(F_S) = q_{thr}. \qquad (2.52)$$

Inequality (2.51) designates the presence of an a priori upper estimate R_S of the maximum amount of information max R at the receiver outlet:

$$R_S = T \int_0^{F_S} \log_2 \frac{q_S^2 K^2(f)}{q_{thr}^2}\, df, \text{ bits}, \qquad (2.53)$$

in which R_S >max R.

An estimate of the upper R_S is calculated from function $q_S K(f)$, which can be called the frequency (spectral) signal-noise ratio from the threshold signal-noise ratio q_{thr} and interval T. These quantities should be known a priori. The intersection of the frequency signal-noise ratio with the threshold value, in accordance with the equation (2.52), determines the band of those frequencies F_S, which can be measured above the noise and, consequently, give useful information about the object. Therefore, be call the frequency band F_s, determined from equation (2.52), the information band. The integral estimate of the excess of the frequency signal-noise ratio over the threshold in the information frequency band is the information characteristic R_s/T measured in binary units per unit interval T (i.e., per second or per millimeter)(Fig. 2.10). A similarity is easily noted between equation (2.52) and the quantity R_s/T from formula (2.53) and equation (2.34) and quantity (2.35), of the ε entropy calculation by an equilibrium random function. The specifics of quantity R_s are that it emerges as the upper estimate of the amount of information on a nonequilibrium continuous message contained in the sum of it with the white noise.

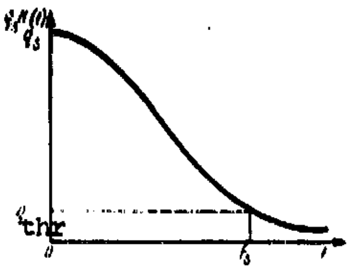


Fig. 2.10 Upper estimate of amount of information

The concept of information frequency band F_s flows from the method of calculation of ε entropy by Kolmogorov (section 2.4), in the event equality (2.41) holds true.[1] This concept can be reached, as a result of a very simple consideration of the effect of noise in the scheme of measurement of the amplitude-frequency characteristics of the low-frequency filters (Fig. 2.11)[47]. The amplitude of the test sinusoids /97

$$\left(\frac{A}{2}\sin 2\pi ft + A_0\right),$$

passing through filter K(f) equals AK(f). Theoretically, it always is measured on a background of noise with power

$$P_n = \int_0^\infty S_n K^2(f)\,df.$$

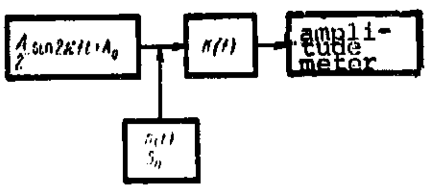


Fig. 2.11 Diagram of amplitude-frequency characteristic measurement in the presence of noise

Because of the noise, the process of measurement of the amplitude sinusoids is probabilistic. The measurement results estimate the trend of the amplitude-frequency curves K(f), within a given confidence interval, which depends on the signal-noise ratio (Fig. 2.12). At zero frequency f_0, the ratio of the sinusoid amplitude to the effective noise value is quite high:

[1]Equality (2.41) specifies that the model with a limited spectrum in work [5] should be understood by the words "not too" small an error in representation of a continuous message. It should be noted that earlier efforts to specify these words resulted in use of the frequency band which is equivalent in power (effective) F_e [48, pp. 4, 111, 143].

$q_S = AK(f_0)/\sqrt{T_n}$. With increase in frequency $f > f_0$, the signal-noise ratio drops according to the $q_S K_H(f)$ rule, where $K_H(f) = K(f)/K(0)$ is the standardized value of the amplitude-frequency characteristic.

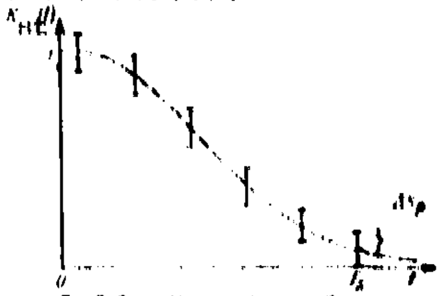


Fig. 2.12 Result of measurement of amplitude-frequency characteristics

At frequency $f = F_S$, the signal-noise ratio reaches the threshold value q_{thr} (Fig. 2.10), at which equation (2.52) holds true: $q_S K_H(F_S) = Aq_{thr}$.

The amplitude of sinusoids with frequencies $f > F_S$, not only cannot be measured, but simply cannot be detected on the background of noise. The final information frequency band F_S, with which transmission of information at a given noise is connected, is determined from conditions (2.52), which we rewrite in the form $K_H(F_S) = \Delta K_p$, where $\Delta K_p = q_{thr}/q_S$.

Interpreting ΔK_p as the confidence integral of measurement at /98 a given probability $P > 0.5$, it can be said that, outside the information frequency F_S, there is a probability $P > 0.5$ of measurement of a zero value of the $K(f)$ characteristic of a filter (Fig. 2.12).

The importance of determination of the information frequency band F_S is dependent on the fact that it shows the sense in which the limited nature of the frequency band can correctly be spoken of, for filters which can be physically created and for real continuous messages. We establish the connection between the correctly determined value of F_S and the conventional frequency band widely used in practice, for example, $F_{0.5}$ or F_{e1}. From equation (2.52), we have for the filter characteristic of the type (2.50)

$$F_S = F_{0,5} \sqrt[\alpha]{\frac{q_S}{q_{thr}} - 1}. \qquad (2.54)$$

Formula (2.54) shows that the difference in the values F_S and $F_{0.5}$ depends on the signal-noise ratio and on the degree α of decrease in the amplitude-frequency characteristic. If $q_S = 100\, q_{thr}$ and $\alpha = 8$, $F_S \sim 1.8\, F_{0.5}$.

Formula (2.54) permits it to be concluded that, in multilink systems, with $\alpha > 8$ and signal-noise ratio $2q_{thr} < q_S \leq 100\, q_{thr}$, the conventional frequency band $F_{0.5}$ used in practice can be the first approximation to the value of the information frequency band F_S.

We transform formula (2.53) to the form

$$R_S = 2TF_S \left| \log_2 \frac{q_S}{q_{thr}} - \Delta R_1 \right|, \text{ bits.} \qquad (2.55)$$

where
$$\Delta R_1 = \frac{1}{F_S}\int_0^{F_S} |\log_2 K(f)|\, df.$$

It is evident from formula (2.55) that the quantity $N_S = 2TF_S$ serves as an a priori upper estimate of the number N_{opt} of receiver storage devices or, which is the same, the number of measurements. The quantity ΔR_1 estimates the loss in amount of information in one measurement, because of a decrease in amplitude-frequency characteristics of the filter. We note that the expression for ΔR_1 coincides with the estimate of entropy loss in the filter, expressed in theorem 14 of Shannon [6, p. 301], but, in distinction from it, it was obtained for filters which do not disrupt the Paley-Viner condition.

Formulas (2.52) and (2.53) give the desired a priori upper estimates of N_S and R_S of the quantities N_{opt} and max R for the case of a priori amplitude-frequency characteristics of the type, for example, of (2.50).

The upper estimates obtained of N_S and R_S permit reformulation of the basic assumption set forth above in the following manner: The optimum receiver, maximizing the amount of information, because of noise, is capable of carrying out only a finite number of measurements of a continuous message, no greater than $2TF_S$, which follows /99 with intervals Δt_S, determined by the information frequency band F_S:

$$\Delta t_S = \frac{T}{N_S} = \frac{1}{2F_S}. \tag{2.56}$$

The amount of information which can be extracted in this case does not exceed the quantity R_S, calculated from formula (2.55), and the resulting quantized image can be represented by series (2.48)

$$\hat{m}_i(t) = \sum_{k=1}^{2TF_S} \hat{m}_{ik}\, g(t - k\Delta t_S). \tag{2.57}$$

The basic assumption formulated, sum (2.57) and formula (2.55) were obtained for the case of a nonsingular model of a continuous message, developed in the works of Kolmogorov and Viner, with noise taken into account. We recall that the theorem of Kotel'nikov, his series (2.19) and the formula of Shannon (2.27) were obtained for a singular model of a continuous message (singular functions). We compare the formulated assumption, sum (2.57) and formula (2.55) with the theorem of Kotel'nikov, his series (2.19) and the formula of Shannon (2.27). The comparison shows that the theorem of Kotel'nikov and the formula of Shannon preserve their meaning, with rejection of the singularity of the function, because the noise produces limited information frequency bands. By simple substitution of the limited band F of the singular function by the information frequency band F_S, we can change from formulas (2.20) and (2.27) to formulas (2.56) and (2.55).

However, the change from series (2.19) of Kotel'nikov to sum (2.57) involves more serious changes. Sum (2.57) does not satisfy the requirement of precise representation of the function received, in distinction from the series of Kotel'nikov (2.19), but it fulfills the requirement of maximization of the amount of receivable information. In connection with this, clarity in selection of unit vectors and simplicity of calculation of the expansion coefficients (readouts) are lost. Readouts in sum (2.57) do not equal the instantaneous values of the function at points $k\Delta t_s$, but "clusters" of energy E_k, accumulated in interval Δt_s, of the function perceived are detected.

2.5 Potential Resolution

The maximum number of readouts (measurements) made by the optimum receiver of continuous messages depends on the energy stored. From this point of view, the potential resolution is an important receiver characteristic.

Depending on the a priori information, the potential resolution can have different definitions, according to different features (criteria) and, correspondingly, different methods of calculation. We will classify two definitions of potential resolution (two methods of calculation, correspondingly) [49].

1. Definition of potential resolution with a priori known pulse shapes, from pulse differences on the noise background (for example, in widths); /100

2. Definition of potential resolution with a priori unknown pulse shape, by so-called Rayleigh or classical characteristics (criteria) of resolution, the presence of a dip in the output response.

The method of calculation of potential resolution of two pulses of a priori known shape has been developed in work [50], as a generalization of the statistical problem of detection. It has already been noted in section 2.3 that optimum reception of the simplest message, of a pulse (in Cartesian coordinates of a spot on a uniform background) can be accomplished with an a priori known position of it, by means of a single matched filter (storage device).

We complicate the message somewhat: Let it coincide with either one unit vector or with two neighboring ones, i.e.,

$$m_1(t) = Ag(t-k\Delta t) + Ag[t-(k+1)\Delta t]. \qquad (2.58)$$

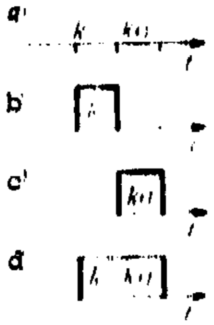


Fig. 2.13 Set of possible messages: a) no message; b) message coincides with k-th unit vector; c) message coincides with (k+1)-th unit vector; d) message coincides with both unit vectors

The positions of the pulses, i.e., the values k and k + 1 are known a priori. Then, the set of possible messages consist of four messages, and it is represented in Fig. 2.13. For the optimum reception of a message (formula 2.58) on a background of noise, it is sufficient to have a storage device consisting of two matched filters. The choice of one of four messages can be made, by means of a signal limiter at the filter outlets, according to the threshold level established by a previously designated probability of a false alarm (the Neumann-Pearson criterion is used). Then, the probability of detection of a pulse is determined by the signal-noise ratio

$$q^2 = 2E_1/S_n$$

where E_1 is the energy of one pulse and S_n is the spectral density of the noise power.

To establish the presence of two pulses, i.e., to resolve two pulses, is possible in this case, when there is no dip between the two pulses, even in the input signal (Fig. 2.13d). Of course, what has been said holds true for message (2.58), when argument t is substituted by Cartesian coordinates (x, y), i.e., for the task of resolution of two adjacent squares (without a dip), on a background of uniform brightness. The possibility of such resolution is easy to test visually. The eye, knowing the width of one square (or line), establishes the fact of the presence of two squares by change in width. The visual analyzer resolves not only two adjacent lines /101
from one, but two overlapping lines. Knowing a priori that the lines have the dimensions shown in Fig. 2.14a, it can be seen immediately that two lines overlapping one another are represented in Fig. 2.14b, as is explained in Fig. 2.14c.

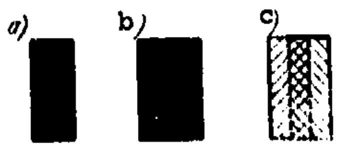


Fig. 2.14 Resolution of two overlapping lines by increment in width (area)

The simple considerations presented on the differences in two overlapping lines (pulses) have been formalized in a method of calculation of the potential resolution developed in work [50, p. 319]. The initial assumptions of this method are the following. A signal enters the receiver inlet, in the form of two overlapping finite pulses on a background of white noise[1] $Ag(t) + Ag(t-\tau) + n(t)$, where A is the pulse amplitude and τ is the distance between pulse centers, no greater than the pulse duration Δt.

The shape of pulses $g(t)$ and their possible positions (i.e., the value $t = 0$ and τ) are known a priori. Their amplitudes and the fact of the presence of pulses are unknown. In accordance with the theory of the optimum receiver, one message of four possible ones might be selected, i.e., two bits of information must be obtained. The specifics of such a receiver depend on the fact that the pulses are not orthogonal, i.e., they overlap. Therefore, two filters, matched only with each of the pulses separately, cannot be used. Matching must also take account of the degree of overlap of the pulses.

Correspondingly, the mutual energy of the two pulses is:

$$E(\tau) = A^2 \int_0^{\infty} g(t) g(t-\tau)\,dt,\quad E(0) = A^2 \int_0^{\infty} g^2(t)\,dt = E_1$$

The degree of overlap, or correlation, of the two pulses is estimated by the correlation function, more precisely, the autocorrelation function,

$$\psi(\tau) = \frac{E(\tau)}{E_1} = \frac{\int_0^{\infty} g(t) g(t-\tau)\,dt}{\int_0^{\infty} g^2(t)\,dt}, \qquad (2.59)$$

since the pulses are identical.

The autocorrelation function is even, $\psi(\tau) = \psi(-\tau)$.

Examples of finite pulses and their autocorrelation functions /102 are given in Fig. 2.15. The following are numerical characteristics of function $\psi(\tau)$

1. Function width at zero level $\psi(\tau_0) = 0$.

   For finite pulses with duration Δt, we have $\tau_0 = \Delta t$. It is evident that pulses shifted by interval Δt are orthogonal.

2. Equivalent width of function

$$\tau_e = \int_0^{\tau_0} \psi^2(\tau)\,d\tau,\quad \tau_e < \tau_0.$$

It was shown in work [50] that the optimum receiver must contain two filters, matched, not simply to each of the pulses, but with consideration taken of the autocorrelation function $\psi(\tau)$ [50, p. 312]. The probability of correct detection of a pulse P_{po} at the outlet of each of the matching filters, with a given probability of a false

[1] The assumption of equality of the pulses simplifies the calculation method.

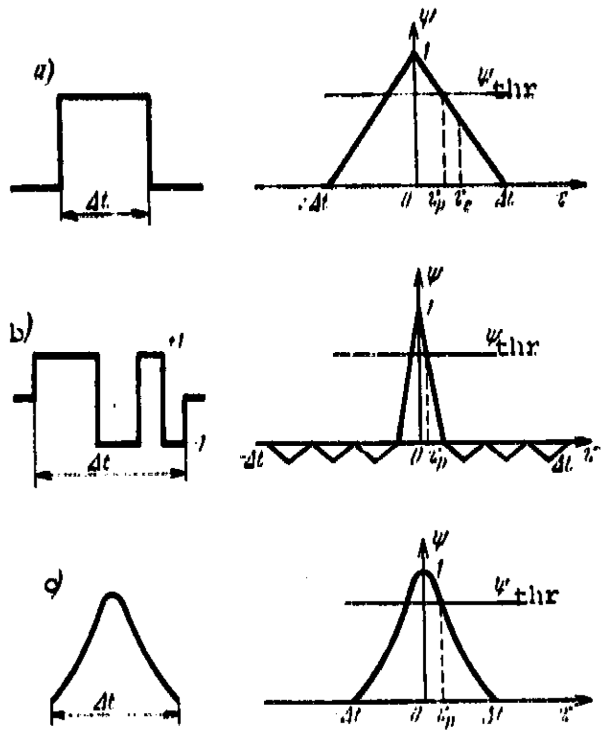


Fig. 2.15 Finite pulses and their autocorrelation functions

alarm, will then be the monotonic function:

$$P_{po} = P\left\{\frac{2E_1}{S_n}[1-\psi^2(\tau)]\right\}. \quad (2.60)$$

Having fixed the detection /103 probability P_{po} = const, we obtain an equation for calculation of the resolution interval τ_p from equation (2.60) [50][1]

$$\frac{2E_1}{S_n}[1-\psi^2(\tau_p)] = q^2_{thr}, \quad (2.61)$$

where q^2_{thr} is a quantity dependent on the given detection probability P_{po}.

Solution of equation (2.61) permits the resolution interval τ_p to be found, i.e., the smallest shift between pulses, at which the receiver can still make a decision on the presence of two pulses on the noise background. The quantity $1/\tau_p$ is a measure of the resolution limited by noise, which can be called the potential, if the definition of Kotel'nikov of potential value is followed [4, p. 10].

The equation of the potential resolving power (2.61) has a very simple explanation. The output signal from two overlapping pulses always differs from the output signal from one pulse. The difference in these two signals depends on the extent of divergence of the pulses. At the output of an optimum receiver, the energy of the difference output signal

$$\Delta E(\tau) = E_1[1-\psi^2(\tau)].$$

It is evident that

$$\Delta E(\tau) = \begin{cases} E_1 & \text{at } \tau \geq \Delta t, \\ 0 & \text{at } \tau = 0. \end{cases}$$

Consequently, the expression on the left in equation (2.61) can be considered as the maximum ratio of the peak difference signal power to the white noise power at the outlet of a filter, matched

---

[1]Although the change from function (2.60) to equation (2.61) and interpretation of this equation is not directly present in work [50], this appears to be evident.

with the difference signal. With a given detection probability P_{po} = const, usually greater than 0.5, this signal-noise ratio must be equal to the threshold ratio q_{thr} (depending on the excess of P_{po} over 0.5), which expresses the mathematical recording in equation (2.61). The interpretation of the resolution interval τ_p as the width of the autocorrelation function flows from equation (2.61). For this, we rewrite it in the form

$$\psi(\tau_p) = 1 - \sqrt{1 - \frac{q^2_{thr}}{q^2_1}}. \tag{2.62}$$

Equation (2.62) shows that the resolution interval τ_p is equivalent to the width of autocorrelation function $\psi(\tau)$ of the input pulse, which can be reckoned from the threshold level (Fig. 2.15): $\psi_{thr} = 1 - \sqrt{1 - q^2_{thr}/q^2_1}$, where $q^2_1 = \frac{2E_1}{S_n}$ is the output signal-noise ratio of one pulse.

It becomes evident from equation (2.62) that the width of the autocorrelation function is a measure of the potential resolution, however, not the equivalent width τ_e, but the width τ_p from the threshold level[1]. /104

To illustrate this conclusion more graphically, we assign a specific form of the autocorrelation function. Examples of function $\psi(\tau)$ are given in Fig. 2.15. For a rectangular pulse, we have

$$\psi(\tau) = \frac{\Delta t - |\tau|}{\Delta t} = 1 - \frac{|\tau|}{\Delta t}, \tag{2.63}$$

where $|\tau| \leq \Delta t$.

Applied to two overlapping rectangular pulses, shifted by τ, difference $\Delta t - |\tau|$ characterizes the change in width, in comparison of a double pulse with one known a priori. Therefore, the quantity (2.63) has obvious meaning as a measure of the relative change in width. In accordance with equation (2.62), for resolution of two overlapping rectangular pulses, a relative change in width must exceed the threshold value ψ_{thr}.

Substituting (2.63) in equation (2.62), we obtain the width of the function from the threshold level

$$\tau_p \approx \frac{\Delta t\, q^2_{thr}}{4 \frac{E_1}{S_n}}. \tag{2.64}$$

---

[1]An estimate of resolution by the equivalent τ_e [51, p. 119] is preserved up to the present time [52, p. 205].

In the general case, even function $\psi(\tau)$ can be expanded in a Maclaurin series and be limited by the first two terms:

$$\psi(\tau) \approx 1 + \frac{1}{2}\psi''(0)\tau^2. \qquad (2.65)$$

Substituting (2.65) in equation (2.62), we obtain[1]

$$\tau_p = \frac{q_{thr}}{\sqrt{\frac{2E_1}{S_n}|\psi''(0)|}}. \qquad (2.66)$$

The solutions of equations (2.64), (2.66) and (2.62) demonstrate graphically that, with a given pulse width Δt, the value of the resolution interval τ_p decreases monotonically with increase in signal-current ratio $2E_1/S_n$.

It follows from equation (2.62) that, in the presence of noise ($S_n > 0$ and $q^2_{thr} > 1$), the increase in energy E_1 of the pulse permits an unlimited increase in the potential resolution, i.e.,

$$\lim_{E_1 \to \infty} \tau_p = 0 \quad \text{or} \quad \lim_{E_1 \to \infty} \frac{1}{\tau_p} = \infty.$$

The absence of a limit to increase in potential resolution is an important singularity in definition of this concept [50], dependent on the presence of much a priori information. 405

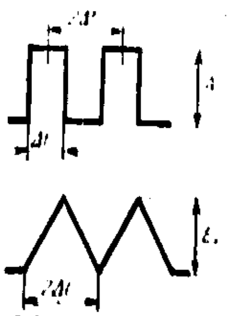


Fig. 2.16 Two-line Foucault globe and its autocorrelation function

A method of calculation of the potential resolution was developed in work [50], for application to radar. It is obvious that its use in television is possible, if the initial requirements for a priori information are satisfied. For example, measurement of the shift of a spot or line, the shape of which usually is known a priori, can be made in a television system, by the criterion of detection of a difference signal. The minimum value of the shift, τ_p, is calculated from equation (2.62). It is of interest to apply the method of Hellstrom [50] to resolution of a lined Foucault globe, by which resolving power usually is measured in television (see section 1.5). The lines in the Foucault globe (Fig. 2.16) refer to orthogonal pulses, since $\psi(\Delta t) = 0$ and, what is more, $\psi(\tau = 2\Delta t) = 0$. From the point of view of the Hellstrom method, resolution of the Foucault globe degenerates into a simple problem

[1]Formula (2.66) coincides with the Woodward formula for dispersion of errors in measurement of coordinates [51, p. 107].

in detection of each line separately. The signal at the outlet of a filter matched with one pulse (line) is shown in Fig. 2.16. It is evident that the amplitude of the dip in the output signal equals the pulse amplitude. The probability of detection of the dip is defined by the signal-noise ratio $2E_1/S_n$. The potential resolution $1/\tau_2$, or the distance between the centers of the lines $\tau_2 = 2\Delta t$, under conditions of threshold detection of a dip, is calculated by the formula

$$\frac{2E_1}{S_n} \quad \frac{2A^2\Delta t}{S_n} \quad \psi^2_{thr}, \tag{2.67}$$

or $\tau_2 \quad \psi^2_{thr} S_n/A^2$.

It is evident that expression (2.67) is a particular form of equation (2.61), at $\psi^c(\tau) = 0$. When the matching filter serves as a photon storage device, taking (2.16) and (1.1) into consideration, it can be written that the ratio

$$2E_1/S_n - k^2N_0 \quad a\Delta l^2BTk^2.$$

Substituting this expression in (2.67), we obtain the well-known formula of Rose [8, 53]:

$$a\Delta l^2BTk^2 \quad \psi^2_{thr}. \tag{2.68}$$

Obtaining the Rose formula as a part of the more general /106
equation (2.61) makes the fact evident that calculations of the limiting resolving power [53] holds true only for filters matched with an a priori known shape of the lines in the measuring globe.

We proceed to examination of the concept of potential resolving power, based on the classical Rayleigh criterion of resolution and to stating a method for calculating it. The classical definition of resolving power arose on the basis of formalization of the process of decoding optical images and distinguishing fine details in them, by means of a television system. The presence of quite a large amount of a priori semantic information is inherent in the process of observation of complex objects, by means of a man decoding received television photos (images). However, there is no a priori nonsemantic information on the shape of the object, generally speaking. There is no a priori information on the shape of fine details of objects being distinguished. In connection with this, the classical criterion of the presence of a dip in the output signal becomes important.

A visual laboratory estimate of resolving power of a television device assumes multiple repetition of measurements, for the purpose of finding the average value of the resolution and the error in measurement. In the initial phase of the measurement process, the observer can acquire information on the shape of single lines. This information can be used as a priori, in the course of subsequent measurements. Consequently, the observer can measure the resolution of two lines, having a priori information on the shape of single lines available, i.e., he can use a nonclassical indication of resolution. Actually, experience confirms the possibility of a correct response of an observer to the presence of two lines and, in those cases when he does not find a dip between the lines, but guesses at the presence of two lines from the width of the image of the globe. However, the method of measurement of resolution of a television (or photographic) device prevents the observer from making a decision on the presence of two lines in the absence of a gap in the image of the globe. The requirement for resolving two lines only by the classical characteristic of detection of a dip is reported to the observer in his instruction before making measurements. This requirement reflects the effort to approximate measurement of resolving power to actual conditions of interpretation of television photos, to conditions in which it is difficult to obtain complete a priori information on the shapes of details being distinguished.

It is clear that, with any pulse (line) shape, if only each of the pulses has one peak, the presence of a dip in the output signal (change in sign of the second derivative of the signal) is an unambiguous indication of the presence of two pulses.

The effect of linear distortions of a filter on pulse trans- /107
mission was reflected as early as the work of Nyquist in 1928 [54]. We illustrate this effect by means of an oscillogram. A double pulse entering the inlet of a low-frequency filter is shown in Fig. 2.17a. The distance between pulse peaks equals double the pulse width ($\tau = 2\Delta t$), as in the Foucault globe. The amplitude-frequency characteristic k(f) of the filter satisfies the Paley-Viner condition, and it has a frequency band equivalent in area

$$F_a = \int_0^\infty K(f)\,df.$$

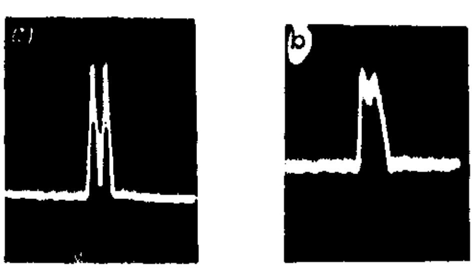


Fig. 2.17 Effect of linear distortions of a filter on pulse reproduction

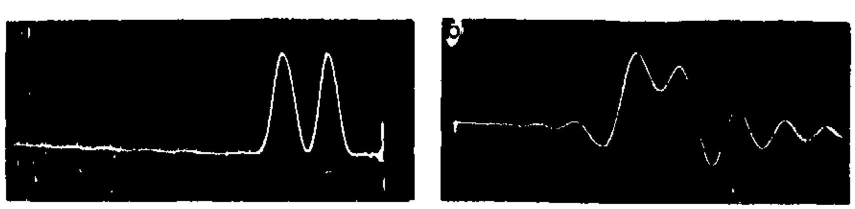
The amplitude-frequency distortions of the filter cause a decrease in pulse amplitude and broadening of it (Fig. 2.17b). This type of distortion depends on the ratio between pulse length and the equivalent frequency band. The condition of "undistorted" pulse transmission was formulated in work [54, pp. 621, 622]; this undistorted nature (proportionality) is understood to be the pulse amplitude, permitting distortion of the pulse shapes. According to the Nyquist condition, the area-equivalent frequency band and the flat and subsequently decreasing amplitude-frequency characteristic of the filter should be equal [54, p. 662]:[1]

---

[1] As applied to telegraph transmission of a sequence of pulses of different amplitudes, the quantity $1/\Delta t$ is called "signalling speed" [54, p. 619].

$$\int_0^{\infty} K(f)\,df \quad \frac{1}{2\Delta t} \tag{2.69}$$

Condition (2.69), in the light of the later concept of depth of a matched filter, can be considered as a condition of incomplete matching (quasimatching) of a filter with an input pulse. A response, which is close to the autocorrelation function represented in Fig. 2.16, will be observed at the output of such a quasimatched filter. The response will have almost a 100% dip between pulses. The presence of a dip is evidence of pulse resolution. However, this does not mean that the condition of pulse resolution has been established, as it asserted in work [3, p. 16], or that the equivalent frequency band F_{e1} can be a numerical measure of resolving power. In fact, the dip in response in a double pulse will be present when this condition (2.69) is violated. The response at $1/2\Delta t > F_{e1}$ is presented in Fig. 2.17b. The situation becomes still more indefinite, if it is not limited by a class of filter, with monotonically decreasing amplitude-frequency characteristics and, as will happen in practice, the possibility of increasing these characteristics at high frequencies is used. Instead of two pulses (Fig. 2.18a), we supply pulses without dips between them to the input of such a filter (Fig. 2.18b). The conclusion would seem to be true that the pulses are not resolved; however, the rise in the amplitude-frequency characteristics of the filter (Fig. 2.19) in the high frequency region restores the dip in the response (Fig. 2.18c). Asymmetrical distortions of pulse shapes and oscillations are caused by the phase-frequency distortions of the filter, which arise in raising the characteristics at high frequencies. /108



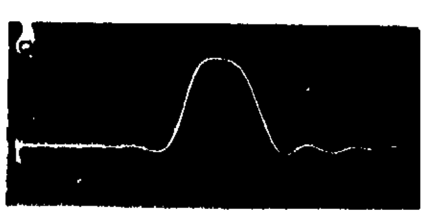


Fig. 2.18 Restoration of dip between pulses, by means of raising the amplitude-frequency characteristics of the filter: a) initial double pulse; b) smoothed output pulses; c) output pulses with restored dip.

The possibility of restoring a smoothed dip is evidence of ambiguity of the classical indication of resolution, the presence of a dip in the output response. It is caused by the fact that, in the absence of noise, the effect of which was not taken into con-

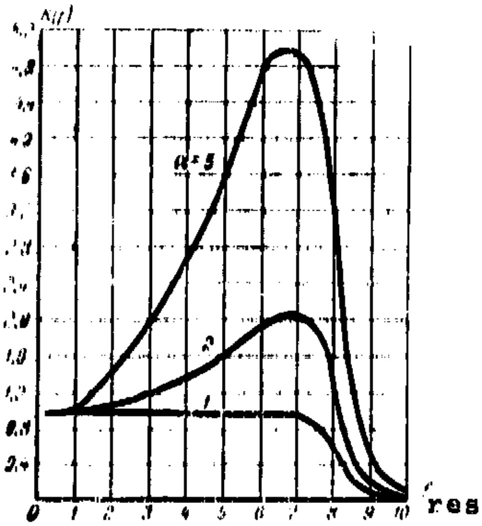


Fig. 2.19 Amplitude-frequency characteristics of filter (video amplifier) with increase in $\alpha = K(f_{res})/K(0)$ in high-frequency region

sideration in the classical definition of resolving power, it will be possible to reach the Rayleigh diffraction limit [55] in any device, by means of restoring the dip.

Precise definition of the classical indication of resolution involves taking the limiting effect of noise into consideration. Overlap of noise in a double pulse masks the dip (Fig. 2.20a) between pulses, which fluctuates. Therefore, the process of detection of a dip between pulses is probabilistic. Superimposition of noise on a double pulse inflicts damage on the dip between them, of only a partially restorable nature. When the dip between pulses is masked by noise, an increase in the characteristics of high frequencies in the filter only partially restores it (Fig. 2.20). A further strengthening of the increase in the characteris- /109
tics only means that the dip is completely "drowned" in the noise.

What has been said leads to a concept of potential resolving power, which is estimated by the least distance between two pulses (two-line Foucault globe), by the criterion of threshold detection a dip on a background of noise. We will call this potential resolution informational, since it has a method of calculation, based on spectral-informational representations [33, 49, 57-59].

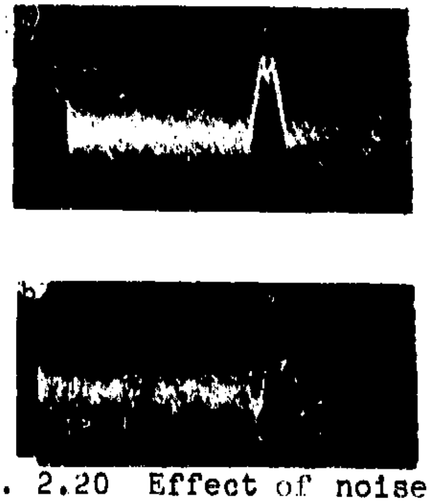


Fig. 2.20 Effect of noise on restoration of dip between pulses: a) smoothed output pulses; b) output pulses with restored dip

We turn to the structural diagram of Fig. 2.21. Two rectangular pulses (an analog of the two-line Foucault globe) are distorted by low-frequency filter $K_1(f)$ and, summed with the white noise, which has a spectural power density S_n, they pass through low-frequency filter $K_2(f)$. The receiver should

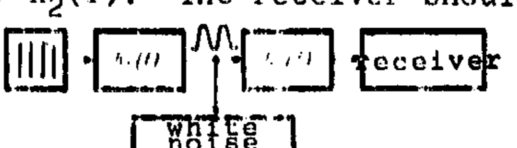


Fig. 2.21 Structural diagram of calculation of potential resolution

record a state of threshold detection of the dip between pulses, i.e., the state of threshold pulse resolution, achieved at the least distance τ_{min} between pulse peaks, from the noisy response at filter $K_2(f)$ output. The information potential resolution $D = 1/\tau_{min} = 1/2\Delta t_{min}$ per./sec(per./mm). We show that the upper estimate of the potential resolving power D is the information frequency band F_S of the filters. /110

At the output of filter $K_2(f)$, the highest ratio of peak pulse power to noise power P_n

$$q_S = \frac{A^2}{P_n} = \frac{A^2}{\int_0^\infty S_n K_2^2(f)\,df}.$$

Knowing a priori the frequency signal-noise ratio q_{max} $K_\Sigma(f)$, we find the information frequency band of the filters from equation (2.52)

$$q_S K_\Sigma(F_S) = q_{thr}, \qquad (2.70)$$

where

$$K_\Sigma(f) = K_1(f) K_2(f).$$

We take the effect of the amplitude spectrum module of two rectilinear pulses into consideration

$$\Phi_2(f) = 2A\Delta t \frac{\sin \pi \Delta t f}{\pi \Delta t f} \cos \pi \tau f, \qquad (2.71)$$

where A is pulse amplitude, Δt is the duration of one pulse, τ equals $2\Delta t$ is the distance between the centers of two pulses.

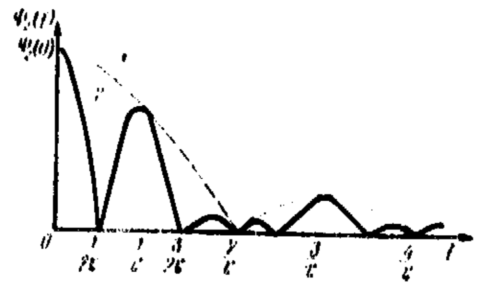


Fig. 2.22 Pulse signal spectrum: 1) one pulse; 2) two pulses

The spectrum $\Phi_2(f)/\Phi_2(0)$ is shown in Fig. 2.22. It has zeros at frequencies $1/\Delta t$, $2/\Delta t$, $3/\Delta t$, . . ., because of the fact that the pulses have a rectangular shape. The presence of two pulses causes the appearance of a cosinusoidal term in spectrum (2.71), which, in turn, causes the presence of the so-called doublet zeros at frequencies $1/2\tau$, $3/2\tau$, $5/2\tau$, ...

At the output of filter $K_2(f)$, on the background of noise, the receiver can measure only finite sections of the spectrum $\Phi_2(f)K_\Sigma(f)$, including all frequencies up to the value F_ε, which can be determined from the equation (2.23):

$$q_S \frac{\Phi_2(F_\varepsilon)}{\Phi_2(0)} K_\Sigma(F_\varepsilon) = q_{thr}. \qquad (2.72)$$

It is evident from a compari- /111
son of equations (2.70) and (2.72)
that

$$F_c = F_s$$

or

$$F_c = \mu_1 F_s, \qquad (2.73)$$

where $\mu_1 \leq 1$ is a coefficient.

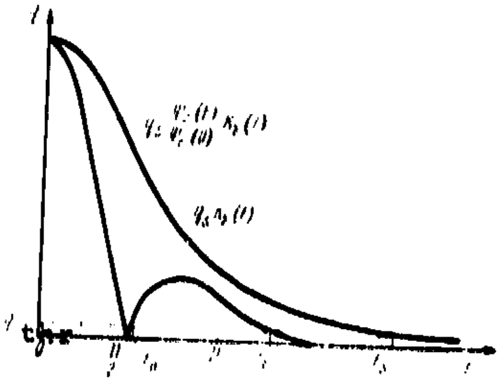


Fig. 2.23 Explanation of calculation of potential resolution

To reproduce the dip between the peaks of two pulses separated by τ, it is necessary (but not sufficient) to reproduce the spectral component with frequency $1/\tau$ (Fig. 2.24). Consequently, the following condition is satisfied in potential resolution of the pulses (Fig. 2.23)

$$D \leq \frac{1}{\tau_{min}} \leq F_c$$

or

$$D = \frac{1}{\mu_2} F_c, \qquad (2.74)$$

where $\mu_2 \geq 1$ is a coefficient.

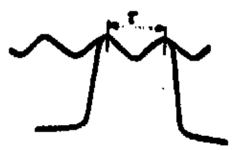


Fig. 2.24 Explanation of necessary condition for resolution of two pulses

Substitution of (2.73) in (2.74) gives the formula

$$D = \frac{\mu_1}{\mu_2} F_s, \qquad (2.75)$$

where $\mu_1/\mu_2 \leq 1$.

Formula (2.75) proves that the information frequency band F_s is an upper estimate of the potential resolution D. Finding of coefficient μ_1/μ_2 in formula (2.75) is a more complicated task.

It is well-known from experience in television that the presence /112
of a dip in the response between pulses is connected with the high-frequency portion of the response spectrum, of which the possibility of restoration of the gap is evidence (Fig. 2.18). Direct instrumental measurement of the response spectrum and comparison of the response shape and its spectrogram show that the appearance of a dip in the response is accompanied by the appearance of a hump on the spectrogram, after the first doublet 0. The width of this hump, measured by the receiver on the noise background, is limited by frequencies F_0 and F_s, which are solutions of equation (2.72) (see Fig. 2.23). The hypothesis might be offered that above-threshold reproduction of the high-frequency portion of the response spectrum at the output of filter $K_2(f)$, with a frequency range (F_0, F_s), is equivalent to detection of a dip in the response. We take into con-

sideration that the amount of information, which resolution of two pulses carries, equals two bits. This assertion can be written in mathematical form, using formula (2.53). According to formula (2.53), the amount of information in reception of the high-frequency section (F_0, F_ε) of the spectrum in interval τ_{min}

$$R(F_0, F_\varepsilon) = \tau_{min} \int_{F_0}^{F_\varepsilon} \log_2 \frac{q_S^2 \varphi_2^2(f)}{q_{thr}^2 \varphi_2^2(0)} K_\Sigma^2(f)\, df, \text{ bits.} \qquad (2.76)$$

The spectral-information conditions of potential resolution is written in the form of the equality

$$\frac{1}{D} \int_{F_0}^{F_\varepsilon} \log_2 \frac{q_S^2 \varphi_2^2(f)}{q_{thr}^2 \varphi_2^2(0)} K_\Sigma^2(f)\, df = 2, \qquad (2.77)$$

where F_0 and F_ε are solutions of equation (2.72), i.e.,

$$q_S \frac{\varphi_2(F_\varepsilon)}{\varphi_2(0)} K_\Sigma(F_\varepsilon) = q_{thr}, \qquad (2.78)$$

$$q_S \frac{\varphi_2(F_0)}{\varphi_2(0)} K_\Sigma(F_0) = q_{thr}, \qquad (2.79)$$

The spectral-informational condition of potential resolution (2.77) can be rewritten in shortened form:

$$2D = R'(F_0, F_\varepsilon), \frac{\text{bit}}{\text{sec}}, \qquad (2.80)$$

where $R'(F_0, F_\varepsilon) = \frac{R(F_0, F_\varepsilon)}{\tau_{min}}$ is the ε entropy of the section of the response spectrum.

Formula (2.80) establishes the fact of equivalence of the potential resolution and the ε entropy of the high-frequency section (F_0, F_ε) of the response spectrum in two test pulses.

Three equations, (2.77), (2.78) and (2.79), form a system of equations for three unknown quantities, D, F_ε and F_0. Solution of the system of equations constitutes the content of the general method of calculation of potential resolution D. A sufficiently precise solution of the equations can be obtained by computer.[1] /113
There is practical interest in an approximate analytical solution. Such a solution was carried out for the system in Fig. 2.21, with the following approximations of the amplitude-frequency characteristics of the filters:

$$K_1(f) = \frac{1}{1 + \left(\frac{f}{F_{0.5}}\right)^\alpha},$$

$$K_2(f) = \begin{cases} 1, & f \leq F_S, \\ -f^{\alpha}, & f > F_S, \end{cases}$$

---

[1] A test of the correspondence of the values of the potential resolving power, calculated by equations (2.77), (2.78) and (2.79), with values obtained by visual evaluation of television images of two-line Foucault globes, was carried out in work [60]. Coincidence of the values confirmed the correctness of the calculation method.

The noise power at the outlet of filter $K_2(f)$ is $P_n = S_n F_S +$

$$+ S_n \int_{F_S}^{\infty} K_2^2(f)\, df = b S_n F_S,$$ where $b > 1$.

The information frequency band equation has the form

$$\frac{q_S}{1 + \left(\frac{F_S}{F_{0.5}}\right)^{\alpha}} = q_{thr}.$$

where

$$q_S = \sqrt{\frac{2 A^2 \frac{1}{2 F_S}}{b S_n}}.$$

With increase in the output signal-noise ratio q_S, the value of F_S increases according to the rule

$$F_S = F_{0.5} \sqrt[\alpha]{\frac{q_S}{q_{thr}} - 1}. \quad (2.81)$$

Omitting the course of approximate solution of the equation, we present the final result, in the form of an approximate formula for calculation of the coefficient

$$\frac{\mu_1}{\mu_2} = \frac{1.1}{\sqrt[\alpha]{c}} \left(1 - \frac{c - 1}{\frac{q_S}{q_{thr}} - 1}\right)^{\frac{1}{\alpha}} \quad (2.82)$$

at $q_S > cq_{thr}$, where $c = 5.27$ for a rectangular pulse shape.

If the output signal-noise ratio is high enough that /114 the condition $q > cq_{thr}$ is satisfied, by taking (2.82) into consideration, formula (2.75) is simplified:

$$D \approx \frac{1}{\sqrt[\alpha]{c}} F_S. \quad (2.83)$$

Formula (2.83) proves the proportionality between the potential resolution D and the information frequency band F_S at sufficiently high output signal-noise ratios. This conclusion has important practical value. It turns out that, to find the potential resolution in the first approximation, it is sufficient to solve the information frequency band equation.

Information frequency band equation (2.70) is written for time filters. Let us see what form this equation takes for a directional filter, which a television camera is. A television camera has directional amplitude-frequency characteristic $K_{dir}(\nu_x, \nu_y)$, determined for directional frequencies in the line-scanning direction ν_x, per./mm, and by frame ν_y. Then, the frequency signal-noise ratio is defined by the function

$$q_s K_{dir}(\nu_x, \nu_y). \tag{2.84}$$

We specify the definition of the signal-noise ratio q_s at the camera output for a large detail, taking the effect of line-scanning contrast and density into account:

$$q_s = \begin{cases} q = q_0 \dfrac{\nu_{z0}}{\nu_z} \text{ at } k \gg 1, & (2.85) \\ q_s = \gamma k q = \gamma k q_0 \dfrac{\nu_{z0}}{\nu_z} \text{ at } k \ll 1, & (2.86) \end{cases}$$

where $k = \Delta B/B_\phi$ is the light contrast of a large detail; $2\nu_z = z/l_\phi$ is the line-scanning density: γ is the steepness (contrast coefficient) of the light curve, represented on the logarithmic scale; q_0 is the signal-noise ratio of a large detail of the greatest contrast ($k \gg 1$), determined at standard line density $2\nu_{z0}$, from the light curve and noise power.

Expression (2.85) reflects the inversely proportional dependence of the signal-noise ratio on line density. Formula (2.86), besides this dependence, takes the drop in video signal current of the camera into consideration, which is proportional to the quantity γk at low contrast ($k < 1$). Taking account of (2.84) and (2.86), equation (2.70), for a television camera, is written in the form

$$k\gamma(B_\phi T)\, q_0(B_\phi T)\, \frac{\nu_{z0}}{\nu_z} K_{dir}(\nu_{Sx}, \nu_{Sy}) = q_{thr}, \tag{2.87}$$

where k is the test **pattern** contrast.

Equation (2.87) connects the single functional dependence of /115
the contrast k, background illumination B_ϕ (exposure $B_\phi T$ is included in the quantities γ and q_0 through the light characteristic), with information directional frequency band (ν_{Sx}, ν_{Sy}) or, which also is in the first approximation, according to (2.83), with the dimensions of a resolvable detail $\Delta\ell_{Sx}\Delta\ell_{Sy} = 1/4\nu_{Sx}\nu_{Sy}$.

The contrast k, background illumination B_ϕ and the area of a resolvable element $\Delta\ell_{Sx}\Delta\ell_{Sy}$, included in equation (2.87), are threshold quantities, since the equation itself reflects threshold resolution conditions, limited by noise. It is evident that, at constant background illumination B_ϕ, the threshold contrast k, perceivable by a television camera, increases with increase in area $\Delta\ell_{Sx}\Delta\ell_{Sy}$ of a resolvable element, because of the decrease in directional amplitude-frequency characteristics.

Equation (2.87) is the basic equation, which formalizes the operation of a television camera as a receiver of light images. Functions $\gamma(BT)$ and $q_0(BT)$, included in equation (2.87), can be obtained in form of light characteristic and noise power calculation tables or curves. For solution of equation (2.87), the type of directional amplitude-frequency characteristic must be made specific. In television, the most widespread method of measurement of resolution by the lined Foucault globe, the lines of which are located perpendicular to the rows and have a larger size in this direction, corresponding to the dimensions of a large detail. In this partial case, the directional amplitude-frequency characteristic degenerates into a unidimensional characteristic $K_{dir}(\nu_x, \nu_y) = K_x(\nu_x)$.

The more general case is resolution of fine details with small dimensions in two directions. Resolution of the squares of a small checkerboard test pattern can serve as an example. In the first approximation, for an isotropic directional amplitude-frequency characteristic, it can be assumed that[1] $K_{dir}(\nu_x, \nu_y) = K_x(\nu_x)K_y(\nu_y) = K^2(\nu)$, in which $K_x(\nu_x) = K_y(\nu_y) = K(\nu)$.

For determination of potential resolution along a line from low-contrast lines, equation (2.87) has the form

$$k\gamma(B_\Phi T)\, q_0(B_\Phi T)\, \frac{\nu_{z0}}{\nu_z} K_x(\nu_{Sx}) = q_{thr}, \qquad (2.88)$$

To estimate the two-dimensional potential resolution ν_S in two directions, for example, by means of a low-contrast checkerboard test pattern, under conditions of isotropy, equation (2.87) is written in the form /116

$$k\gamma(B_\Phi T)\, q_0(B_\Phi T)\, \frac{\nu_{z0}}{\nu_S} K^2(\nu_S) = q_{thr}, \qquad (2.89)$$

in which $\nu_{Sx} = \nu_{Sy} = \nu_S$ and $\nu_z = \nu_S$.

The quantity ν_S is a numerical measure of the specific potential definition of a television image. It equals the maximum line density ($\nu_S = \nu_z$), at which the maximum image definition is achieved, with equal potential resolution along and across the lines ($\nu_{Sx} = \nu_{Sy} = \nu_S$).

Equations (2.88) and (2.89) can be solved for any of three unknowns (k, B_Φ, ν_S), on the assumption of the other two being fixed. For calculation of the potential resolution and specific definition, the equations must be solved for the information frequency band. The solution is easily obtained by using approximation (2.50):

---

[1]More precisely and with the anisotropy of the function taken into consideration, values lying between $K^2(\nu)$ and $K(\nu)$ can be given.

$$K(\nu) = \frac{1}{1+\left(\frac{\nu}{\nu_{0.5}}\right)^{\alpha}}. \qquad (2.90)$$

An amplitude-frequency characteristic of the (2.90) type has an equivalent frequency band

$$\nu_e = \int_0^{\infty} \frac{d\nu}{1+\left(\frac{\nu}{\nu_{0.5}}\right)^{\alpha}} = \nu_{0.5}\int_0^{\infty}\frac{dx}{1+x^{\alpha}}.$$

At $\alpha \geq 2$, the values of ν_e and $\nu_{0.5}$ differ by no more than $\pi/2$.

By substituting approximating function (2.90) in equation (2.89), we obtain

$$k\gamma q_0 \nu_{e0} \frac{1}{\nu_S\left[1+\left(\frac{\nu_S}{\nu_{0.5}}\right)^{\alpha}\right]^2} = q_{thr}.$$

By using the working section of the camera light characteristics, the value of ν_S can be greater than, equal to or less than the value of $\nu_{0.5}$, because of the decrease in detail contrast. In the partial case, when $\nu_S = \nu_{0.5}$, the equation is simplified:

$$k\gamma q_0 \nu_{e0} \frac{1}{4\nu_{0.5}} = q_{thr}. \qquad (2.91)$$

At adequate detail contrast values, when $\nu_S^{\alpha} \gg \nu_{0.5}^{\alpha}$, the units in the denominator can be disregarded and the equation transformed to the form

$$k\gamma q_0 \nu_{e0} \frac{\nu_{0.5}^{2\alpha}}{\nu_S^{2\alpha+1}} = q_{thr}. \qquad (2.92)$$

We find the solution of equation (2.89) from (2.92): /117

$$\nu_S = \nu_{0.5}\left(\frac{k\gamma \nu_{e0} q_0}{\nu_{0.5} q_{thr}}\right)^{\frac{1}{2\alpha+1}} \quad \text{at} \quad \nu_S^{\alpha} \gg \nu_{0.5}^{\alpha}. \qquad (2.93)$$

By substituting (2.90) in equation (2.88) and carrying out similar transformations, we obtain the formula for calculation of the potential resol   of a television camera along a line, for values of $\nu_{Sx} > \nu_{0.5}$:

$$\nu_{Sx} = \nu_{0.5}\left(\frac{k\gamma \nu_{e0} q_0}{\nu_e q_{thr}}\right)^{\frac{1}{\alpha}}. \qquad (2.94)$$

It is evident that, for determination of ν_{sx} by lines of the greatest contrast ($k \gg 1$), with (2.85) taken into consideration, the following calculation formula holds true:

$$\nu_{sx} = \nu_{0.5}\left(\frac{\nu_{z0} q_0}{\nu_z q_{thr}}\right)^{\frac{1}{\alpha}}.$$

We compare formulas (2.93) and (2.94). For large values of α, the values of ν_s and ν_{sx} will be close to the conventional frequency band $\nu_{0.5}$. However, in practice, small values of α are possible, lying in the range $2 \leq \alpha < 3$. For a numerical example, we take the value $\alpha = 2$. Then, at $q_0 = 100\ q_{thr}$ and $\nu_z = \nu_{z0}$, the potential resolving power along the line ν_{sx}, determined from a globe of the greatest contrast, will be 10 times greater than $\nu_{0.5}$. At the same values $\alpha = 2$ and $q_0 = 100\ q_{thr}$, but with low contrast, $k = 0.2$ and $\nu_z = \nu_{0.5}$, $\gamma = 1$, we obtain the potential definition ν_s from formula (2.93), $^{0.5}\sqrt{100 \cdot 0.2} =$ 1.8 times greater than the value of $\nu_{0.5}$ overall. The example introduced again confirms that the conventional frequency band $\nu_{0.5}$ or the Nyquist equivalent frequency band ν_e can be only the first approximation to the resolving power under specific conditions.

In concluding this section, we briefly summarize the general outlines and differences in the methods examined of calculation of the potential resolving power. In both methods, the potential resolution of two pulses is determined by the threshold detection on a noise background of one indication of resolution or another: Detection of the relative increment in width or detection of a dip. The difference in the resolution indicators is a consequence of the difference in amount of a priori information. When the pulse shape (for example, a rectangular pulse) is known a priori, the relative change in response width can be used as an indicator of resolution. This indicator ceases to function, if the pulse shape is not known a priori. Then, one must change to the Rayleigh (classical) indicator of resolution.

A numerical estimate of the potential resolution is carried out, according to the width of the autocorrelation function, or amplitude-frequency characteristic, which are known a priori.

In both cases, the width is calculated from one special read-out level or the other, depending on the output signal-noise ratio. /118
With increase in the output signal-noise ratio, the potential resolution increases monotonically. However, the limit of increase differs, depending on the resolution indicator. The increase in potential resolving power by the Rayleigh indicator, as applied to direction (i.e., D measured in period/mm), has the Rayleigh diffraction limit. A two-line Foucault globe cannot be resolved, if the distance between the line centers is less than the wavelength of the monochromatic light illuminating the globe.

With the pulse-shape known a priori, the increase in potential resolution has no limit. It becomes possible to resolve two lines, shifted to a distance equal to fractions of the wavelength of light and to a zero limit (with expenditure of infinite energy).[1]

2.6 Optimum Television Camera

The theory of receiving continuous messages stated permits determination of an ideal (optimum) receiver of light energy in television, the optimum television camera, which forms an electrical video signal, carrying the maximum amount of information on the optical image input.

The optimum camera contains one energy storage device (matching filter), only in the partial case of tracking a spot of an a priori known shape and position on a background of uniform brightness. A camera intended for the mode of tracking a previously found point object, for example, a star, has one energy storage device. The tracking mode is widely used in radar [52]. It is known that, in this mode, a system with one storage device (matching filter) accomplishes storage of signal energy in an optimum manner. In television, the optimum tracking mode receiver, with a single-element storage device (quasi-matching), a filter, is produced relatively easily, in the form of an optical mechanical camera or a dissector camera.

The task of building an optimum receiver in television is significantly complicated, for the case of receiving the simplest image /119 (a moving spot, with position on the bright background not known a priori), especially for the case of receiving a complicated image. The optimum camera for receiving the simplest image should contain a mosaic of identical energy storage devices, i.e., a set of filters, matching or, which is adequate for practice, quasi-matching by band and storage time.

We write general equation (2.89), for a camera which is quasi-matched with the simplest image

$$k\gamma\, |\psi_0 v_{z0}|_{qm} \frac{1}{v_{zqm}} K^2(v_{zqm}) \quad \psi_{thr}. \qquad (2.95)$$

---

[1]Up to the present, there is no definition in the literature of resolution by two different resolution indicators, the contrast of which is incorrect. Experiments are impossible, which concern potential resolution with a priori known pulse shape, which are considered not in accordance with the Rayleigh concept of resolving power [42, p. 325] and, on this basis, efforts are being made to define the concept of resolving power "free of the shortcomings inherent in the Rayleigh criterion" [42, p. 326], in place of which the Hellstrom method is used for this purpose [50].

For a quasi-matched camera, the quantity $q_0\nu_{z0}$ and line density ν_{zgm} must be found in equation (2.95). It is known that a quasi-matching filter has an equivalent frequency band, equal to the equivalent width of the pulse amplitude spectrum. We consider that, for a filter with characteristics (2.90), the equivalent frequency band is close to $\nu_{0.5}$, and the equivalent spectrum width of a rectangular pulse is close to the inverse value of the pulse duration. This permits the condition of quasi-matching of the camera storage band with the spot area to be written in the form

$$\nu_{0.5} = \frac{1}{\Delta l}, \qquad (2.96)$$

where Δl^2 is the spot area.

A camera, quasi-matched in accordance with (2.96), should have number of lines

$$z_{qm} = \frac{l_\phi}{\Delta l} = \nu_{0.5} l_\phi, \qquad (2.97)$$

where l_ϕ^2 is the camera photo layer area.

Selection of the line density by formula (2.97), i.e., $\nu_{zgm} = \nu_{0.5}/2$, practically eliminates the effect of amplitude-frequency distortions:

$$K^2(\nu_{qm}) = K^2\left(\frac{\nu_{0.5}}{2}\right) \approx 1. \qquad (2.98)$$

The quasi-matching condition expresses the condition of the best light energy storage device. They should include allowance for summing all photons in the exposure time. This allows the following quantity to be found

$$2q_0\nu_{z0} = \sqrt{aB_\phi T}, \qquad (2.99)$$

in which

$$T = \frac{\Delta l}{v_0} = \frac{1}{\nu_{0.5} v_0}, \qquad (2.100)$$

where v_0 is the rate of movement of the spot over the camera photo layer.

By substituting (2.97), (2.98), (2.99) and (2.100) in equation /120
(2.88), for a quasi-matched camera, we obtain

$$k\gamma(B_\phi T) / \sqrt{\bar{a}B_\phi T}\,\frac{1}{\nu_{0.5}} = q_{thr} \qquad (2.101)$$

Equation (2.101) is no other than Rose equation (2.68), obtained from more general equation (2.89), for the quasi-matching condition. The light sensitivity of a quasi-matching camera can be estimated by the value of the threshold contrast, calculated, with (2.96) and (2.100), from (2.101):

$$k_{thr} = \frac{q_0}{\gamma(B_\phi T) + aB_\phi\sqrt{T}}. \qquad (2.102)$$

The assumption of the equality $\gamma = 1$ over the entire exposure range is too much idealized. In the best case, it can be assumed for a television camera that

$$\gamma(BT) = \begin{cases} 1 & \text{at} \quad BT \leqslant (BT)_{gr} \\ 0 & \text{at} \quad BT > (BT)_{gr} \end{cases}$$

A decrease in the contrast coefficient γ to zero, because of the finite capacity of the storage device, sets a limit to reduction in the threshold contrast (2.102) with increase in illumination B_ϕ.

A complex image can be represented as consisting of spots (details) of different areas and different configurations. It is evident that, in this case, the optimum receiver must have an adaptive directional amplitude-frequency characteristic. This possibility is not available as yet to television technology. Therefore, only a suboptimum receiver (camera), having a constant number of elementary storage devices with uniform areas can be brought into being. Such a receiver will be quasi-matched only witn area-average details (spots). Reception of large and small details of a complex image will be carried out in a nonoptimum manner, i.e., with loss of energy. However, if large parts, although with loss of energy, are reproduced by the camera, the smallest details are drowned in the noise, both because of the small amount of their energy and because of the nonoptimum nature of the devices for storing their energy. Therefore, for reception of complex images, television has available only a suboptimum camera, receiving a complex image with the maximum amount of information per frame. For such a suboptimum camera, with a constant amplitude-frequency characteristic (formula 2.90), the number of lines $z_S > z_{0.5}$ can be determined from equation (2.89), by formula (2.93):

$$z_S = 2\nu_S l_\phi = z_{0.5}\left(\frac{k\gamma\nu_{z0}q_0}{\nu_{0.5}q_{thr}}\right)^{\frac{1}{2\alpha+1}}. \qquad (2.103)$$

where $z_{0.5} = 2\nu_{0.5}l_\phi^2$ and l_ϕ^2 is the vidicon photo layer area. The choice of number of lines by formula (2.103) provides for ob- /121
taining an amount of information in a television frame R_S, in accordance with formula (2.55):

$$R_S = z_S^2\left|\log_2\frac{q_\Lambda}{q_{thr}} - \Delta R_2\right| \text{ bits}, \qquad (2.104)$$

where q_Λ is the signal-noise ratio determined by formula (2.86), and

$$\Delta R_2 = \frac{1}{\nu_{Sx}\nu_{Sy}}\int_0^{\nu_{Sx}}\int_0^{\nu_{Sy}} |\log_2 K_{thr}(\nu_x, \nu_y)|\, d\nu_x d\nu_y.$$

Without taking losses in amount of information ΔR_2 into consideration, an estimate of the maximum amount of information per frame, by formula (2.104), becomes especially simple: It is reduced to the product of the potential definition z_S^2 and the logarithmic signal-noise ratio.[1]

Calculation of the number of lines z_S of a suboptimum camera requires numerical values of the quantities a and $\nu_{0.5}$, which can be determined from the directional amplitude-frequency characteristics and the dependences of γ and q_0 on exposure, which, in turn, are determined from the light characteristics. Finding the dependence of the signal-noise ratio q_0 on exposure BT is simplified by allowing for summing all incoming photons (the Rose condition), when formula (2.99) is true. By substituting (2.99) in equation (2.92), we obtain

$$k\gamma(B_\phi T)\sqrt{aB_\phi T}\,\frac{\nu_{0.5}^{2\gamma}}{2\nu_S^{2\gamma+1}} = q_{thr} \qquad (2.105)$$

The difference between equation (2.105) and equation (2.101) is caused by the fact that resolvable details of area $1/4\nu S^2$ are far from the quasi-matching condition (2.96) and, therefore, the dip between them is strongly suppressed by the directional amplitude-frequency characteristics of the camera.

An important question in building a camera, which is quasi-matched with the simplest image or accomplishing suboptimum reception of complex images, is choice of a method of reading out stored video information. In television, the stored, primary video information is read out sequentially in time T_{ro}, with the time video signal forming from the information time video frequency bands /122

$$F_v = \nu_S v_{ro} = \frac{z_S^2}{2T_{ro}},$$

where v_{ro} is the rate of uniform movement of the readout spot over a line on the photo layer.

The rate of input of information from the camera to the communication lines is R_S/T_{ro}, bit/sec.

---

[1]In television, definition and signal-noise ratio of a large detail, expressed in decibels, has long since been acknowledged to be the primary indicator of technical quality of television images. Formula (2.104) shows that the product of these quantities serves as estimate of the maximum amount of information in a television image, with, however, the significant specification that the potential definition, calculated by formula (2.103), previously unknown in television, is kept in mind. In this manner, it is natural that numerous objections against use of amount of information in television, as a measure of technical (nonsemantic) quality of television images, becomes superfluous.

Choice of the optimum value of the time readout is a complicated problem, in which a number of factors must be taken into consideration. Let us examine these factors.

From information contained in television frames, a decision can be made automatically, by means of a resolver, which is part of the optimum camera. As was noted in section 2.2, a camera with a resolver is completely practicable, in reception of the simplest images (see section 3.4). In the case of reception of complex images, the function of the camera is reduced only to transmission of information by communications lines to a man. Television information may be intended for scientific interpretation (for example, study of the Moon or Mars), which is accomplished by man over a long period of time. The interpretation time is not limited by the increase in readout time, for purposes of increasing radio communications range. However, television information can be intended for operational control of a spacecraft by man (control of Lunakhod-1). In this case, the time for making an operational decision T_{dec} is an upper limit of increase in readout time, i.e., $T_{ro} \leq T_{dec}$.

The requirement for increasing radio communications range with the smallest power and radio transmitter dimensions involves decrease in the video frequency band F_S. At sufficiently high definition z_S, this requirement is accompanied by a maximum increase in readout time, i.e., choosing $T_{ro} = T_{dec}$. The time of an operational decision in only one partial case can coincide with the readout time $T_{ro} = 0.04$ sec, selected in broadcast television. Coincidence of the readout time T_{ro} and exposure time T_e also is a partial case. In the general case, exposure (accumulation) time is determined by the dynamics of the object observed. The dynamics of an object observed, in the simplest case of uniform unidirectional motion, can be characterized by the flight time of the camera field of view $T_{fl} = \ell_0/v_0$, where v_0 is the rate of movement of the optical image of an object on the photo layer.

To achieve resolving power ν_S, a shift of the image is permitted in exposure time T_e, only by the resolution interval $1/2\nu_S$. This /123
means selection of exposure time z_S less than the flight time:

$$T \quad \frac{1}{2\nu_S v_0} \quad \frac{T_{ro}}{z_{S\,ro}}.$$

Making readout time equal to exposure time in a television observation, for example, of a moving star, permits the entire trajectory of its movement to be reproduced. However, it is well-known from radar experience that such a reproduction carries excess information for making a decision: Reproduction of individual points of the trajectory is sufficient. Selection of a readout time from the consideration specified $T_{ro} > T_e$ leads to transmission by the optimum camera of a sequence of television frames, the semantic correlation between which, although it exists, is significantly less than in a broadcast television system. The method of selection of the interval between frames, based on considerations of increasing communications range, was proposed by S. I. Katayev [61, 62], as early as 1934, i.e., before the appearance of recommendations on selection of readout time (coverage time) in radar.

Thus, we reach the conclusion that the optimum television camera is an adaptive, slow-scan camera.[1]

---

[1]It should be noted that introduction of the concept, which is important for space television practice, of the optimum camera is based on the works of V. A. Kotel'nikov [4], A. N. Kolmogorov [5] and S. I. Katayev [61]. Questions of building adaptive television systems are considered in works [63, 64].

3. SLOW-SCAN METHOD OF TRANSMISSION OF TELEVISION INFORMATION FROM SPACE

3.1 Slow-scan Method of Compression of Television Signal Spectrum

Compression of the frequency band in transmission of images, /124
with simultaneous increase in resolution above the values achievable in broadcast television, is a primary tendency in planning systems for scientific research in space. The theoretical possibility of finding such methods of compression of the frequency band involves limitation on image diversity. An approximate estimate of the amount of information in a discrete model of an image, consisting of $N = 10^6$ elements,[1] in each of which there are $\bar{S} = 10$ halftones on the average, corresponds, by the formula of Hartley, to selection from $\bar{S}^N = 10^{1\,000\,000}$ diverse images. Image diversity evaluated by the number $10^{1\,000\,000}$ is gigantically large. A television system, planned for transmission of such a diversity of images, i.e., transmitting amount of information $I = 10^6 \log_2 10$ bits in 0.04 sec, has a throughput capability of $70 \cdot 10^6$ bit/sec. However, it is known that the measured throughput capability of the visual analyzer is 70 bit/sec, i.e., one millionth of that presented above. The explanation of this should be sought in the perfection of the visual apparatus achieved in the historical process of development of the visual analyzer. Adaptation of man to life under terrestrial conditions has involved the strongest limitations on the variety of images, reproduction of which was necessary for life. The result of benefiting from the limitation of image diversity was expressed in reduction of throughput capability of the visual analyzer by a million times, compared with the method of image transmission not applying these limitations.

The mechanism of limitation of image diversity in the visual analyzer, the higher section of which is the brain, is unknown.
It is difficult to expect that the visual analyzer would use only /125
the simplest form of limitation of diversity, which is manifested in simple recurrence of signals, for example, in recurrence of the brightness values in neighboring elements. It is more likely that there are deep-seated semantic limitations on image diversity in the visual analyzer. The expression of N. Viner on the auditory analyzer might refer to the visual analyzer: "The semantic receiving apparatus receives and translates language, not word by word, but idea by idea and, frequently, in even more general form. In a certain sense, this apparatus is capable of recalling all transformed

---

[1]The discreteness of the light-sensitive layers in the visual analyzer and in the better television systems is evaluated by a number on the order of 10^6.

past experience, and these long transmissions make up a considerable part of its work" [65, p. 89].

Everyday experience is evidence of a greater interference-protection of perception of semantic messages by man, compared with nonsemantic ones. The use of semantic connections in images for increasing interference protection of reception is a virtue, at the present time, of only the higher sections of the visual analyzer, of the brain.

While use of a semantic limitation on image diversity (semantic excess) for reduction in throughput capability and to increase interference protection of reception is a problem, which has been solved in the visual analyzer, this is a scientific problem in communications technology. Not having a mathematical apparatus which permits evaluation of semantically significant information, it naturally is impossible to estimate the degree of efficiency of the methods of use of semantic excess in messages in communications systems. However, this does not exclude the possibility of benefiting from taking semantic connections into account at the present time. A specific example of such a benefit is the slow-scan method of compression of the transmission band in transmission of television images [61, 62, 66 - 69].

A comparison of neighboring frames transmitted in broadcast television and in motion pictures demonstrates a very slow change of subject. Tens and hundreds of frames have essentially the same semantic content. An abrupt change in subject in neighboring frames most frequently is not a reflection of reality, but the result of intervention by the director in the transmission of natural images. In placing a story of the lives of his heroesin various cities and countries and different times of day and year within the framework of a one-and-a-half hour showing, the director resorts to the artificial procedure of abrupt changes in semantic content of the images being shown.

Estimating the semantic recurrence in television frames is complicated in the general case. We make an approximate estimate of the semantic recurrence of frames in the partial case, but an important one for the uses being considered, of observation of the surface of a planet by a television camera from some carrier moving forward at constant speed (Fig. 3.1). The field of view of the camera encompasses an area on the surface of the planet, in the shape of a /126
square, with side $\ell = \ell_0 H/\ell_{foc}$, where ℓ_0 is the side of a square area of the photosensitive layer of the camera, ℓ_{foc} is the focal length of the lens and H is the flight altitude.

As a consequence of the relative displacement of the camera and the observed surface, the optical image moves along the photosensitive layer of the camera at constant speed v_0, mm/sec.

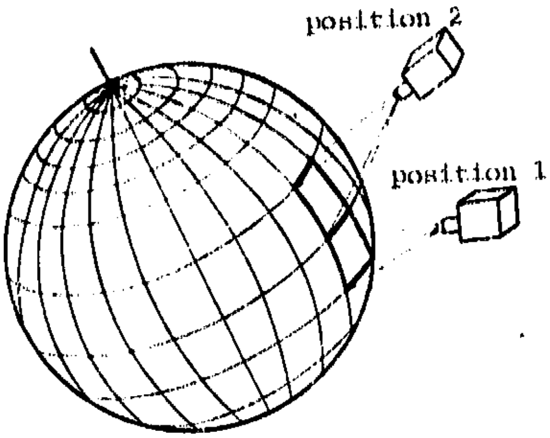


Fig. 3.1 Explanation of slow-scan method of television signal spectrum compression

We consider the case, when an observation is made by the transmitting camera of a broadcast television system. The exposure time in broadcasting systems equals the frame time $T_e = T_{fr} = 1/25$ sec. The optical projection of the image moves distance $v_0 T_e$ mm in the exposure time. In order for the loss in resolution in this case not to exceed permissible values, the amount of shift also should not exceed permissible values, i.e.,

$$v_0 T_e \leq \tau \qquad (3.1)$$

where τ is the distance between two resolvable lines.

In satisfying condition (3.1), the content of each successive frame differs little from that of the preceding one. We calculate the number of frames n_{fr} or the time interval $n_{fr}T_{fr}$ sec, in which the subject in the frame changes completely, i.e., the time interval, in which the camera moves from position 1 to position 2 (Fig. 3.1):

$$n_{fr} = \frac{l_\phi}{v_0 T_{fr}} \geq \frac{l_\phi}{\tau_{fr}}.$$

For a broadcast television system, it can be considered in the first approximation that the value $n_{fr} \sim 600$ is correct. We then obtain $n_{fr}T_{fr} \sim 24$ sec. The resulting figures give an approximate/127 lower estimate of the semantic recurrence of frames, reproduced with the necessary resolving power by a broadcast television system. The time for complete change of subject of a frame $T_{sem} = n_{fr}T_{fr}$ can be interpreted as the mean interval of interframe semantic correlation.

The question arises: Why was a frame rate of 25 Hz chosen in television broadcasting, with such a large semantic correlation interval $T_{sem} \geq 24$ sec? Television broadcasting does not pursue the goal of efficient video information transmission. Selection of the frame rate of 25 Hz is necessary for creating the illusion of fusion in transmitting motion and to eliminate flickering of the image in visual observation of it on television screens. It should be noted that, with this choice of frame rate, no advantage is gained from the semantic recurrence of frames for correctly building television apparatus.

If flickering of television images and loss of the illusion of fusion is permitted in transmission of the movement of objects, the semantic recurrence of the image can be used for compression the time frequency transmission bands in space television video and radar systems, by means of the so-called slow-scan method.

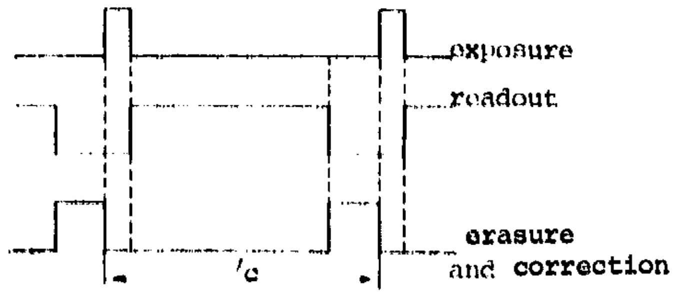


Fig. 3.2 Operating cycle of transmitting tube in slow-scan method

The essence of the slow-scan method consists of storage and transmission of only those images which significantly differ in semantic content. For this, the transmitting camera in the slow-scan method operates on a cycle, the time of which is established by equal times of change in content in the scene being observed. The cycle time T_c is divided into three intervals: The exposure time T_e necessary for accumulation of video information on the camera tube target, the readout time of video information stored in the memory T_{ro} and the time for erasure and preparation of the target for accumulation of new video information T_{pr} (Fig. 3.2). Slow-scan systems must have automatic regulation of the cycle time T_c, tracking the rate of change of sensory content of the image. However, slow-scan systems with constant /128 cycle time (or with programed cycle-time changing) are widespread at the present time. These systems are designed, on the basis of a priori information on the rate of change of sensory content of images of the natural scene being studied.

The possibility of compression of a television spectrum by the slow-scan method depends on the rate of change in semantic content, which is very much less than the rate of the mechanical movement in observation of natural scenes, as a rule. The rate of mechanical movement of observed objects determines the permissible shift in the optical projection of the image, in conformance with formula (3.1), i.e., it determines the exposure time T_e at a given resolution. The rate of change in semantic content of the image determines the operating cycle time of the transmitting camera.

The excess of the cycle time T_c over exposure time T_e permits the readout process to be slowed down and, thereby, the video signal spectrum to be compressed.

A narrow-band, slow-scan video signal from a moving natural scene was first obtained, by means of iconoscope and supericonoscope type camera tubes, by S. I. Katayev, in 1934-1938 [61]. However, the slow-scan method was not widespread in those years. It was turned to again in the 1950's, in connection with the necessity for solution of the problems of increasing the range of television transmission from space, facilitating conditions for preservation of the video signal aboard spacecraft, insertion of television signals into computers, etc. [66 - 69]. The use predominantly of vidicon type camera tubes, having semiconductor film storage devices, in space systems, required investigation of the process of formation of a slow-scan video signal, as free as possible of noise, with acceptable exposure and resolution.

The most important problems, clearing up of which was necessary for designing slow-scan space systems, are the following:

-- Evaluation of the capacity of film storage devices (including semiconductor ones) for rapid accumulation and long memory;

-- Investigation of the possibility of efficient noise suppression in the slow-scan video signal and increasing resolution of the system;

-- Finding a method for decreasing the time of erasure of stored video information and preparation of the target for accumulation of new information in vidicon type camera tubes.

The remaining sections of this chapter are devoted to solution of these problems.

3.2 Memory Length and the Storage Process in Camera Tubes

One of the first problems which should be solved by slow-scan system planners is the selection of the time interval of readout from the memory. For a correct selection of the interval, in which the /129
camera tube is capable of forming a video signal, the length of its memory must be known. Memory is what we call the capability of a camera tube to preserve a charged image in the storage time during exposure, under conditions, when the shutter is closed, the electronic readout beam is "closed" by a negative voltage on the Wehnelt cylinder, and the voltages on the remaining electrodes of the camera tube are set in accordance with its nameplate data. Under these conditions, the charges on the camera tube target spread over the surface and flow off onto the signal plate. The charge spreading time is determined by the surface resistivity of the target. Spreading of the charges over the surface of the target, causing loss of camera tube resolution, is even observed in iconoscope and supericonoscope type tubes, which have a dielectric target of mica. The cause of the surface leakage of the charges in such tubes is formation of a layer with reduced resistance on the surface of the target, by virtue of technological features of iconoscope and supericonoscope fabrication [2]. Superorthicon and vidicon type camera tubes have semiconductor targets. These tubes accumulate charges quite effectively in 1/25 sec; it can be assumed that their semiconductor targets have a memory of at least a tenth of a second. However, more precise estimates of the memory length are necessary. This is the more so, for the cause of erasure of a charged image on the target can be, not only a low target resistance, but residual gases and various types of stray emissions in the camera tubes. In the supericonoscopes and superorthicons, there still is photocathode electron thermal emission with

the shutter closed, which erase the latent image.[1] With the readout beam shut off, but with the incandescent thermocathode switched on, penetration of light from the incandescent filament to the target is possible, as a result of which, the latent image is erased, not only on the light-sensitive targets of the vidicon, but on the super-iconoscope and superorthicon targets, which have a weak sensitivity to spurious light. Penetration of scattered light to the camera tube is possible, because of inadequate sealing of the camera and through the photo layer.

The method of recording the memory length characteristics of camera tubes, applicable to all types of tubes, consists of the following [70, 71]. The time interval between the end of the exposure and start of readout τ_3 is made adjustable, by means of one of the time-delay systems of the pulse controlling the start of exposure and readout (Fig. 3.3). The processes of exposure of test pattern 0249 and readout are repeated, with gradually increasing values of τ_3. The video signal in the first line, read out over a time equal to /130
τ_3 after exposure, is measured on an oscillograph screen. The decrease in video signal amplitude with increase in delay time reflects the retainability of the "latent" image stored on the target over time, i.e., camera tube memory.

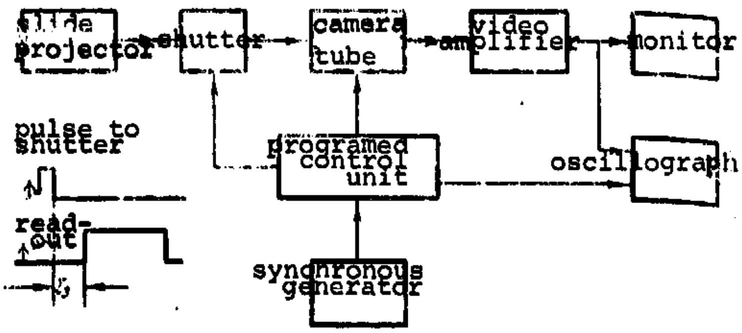


Fig. 3.3 Structural diagram c. camera tube memory time measurement

The characteristics of the memories of various types of camera tubes, measured by the method described, are presented in Fig. 3.4. Decrease in amplitude of the video signal from a large detail is plotted on the ordinate in per cent. Having fixed the latent image intensity by the permissible decrease, it is easy to determine the longest readout time from the memory in a slow-scan system, which is achievable in operation of a given type of camera tube, from the memory length characteristic. As should have been expected, the tube with a dielectric target, the supericonoscope, has the longest memory length. Vidicons with semiconductor targets had a shorter memory length, depending on the resistivity of the semiconductor and their manufacturing technology.

In the slow-scan method of image transmission, an optimum exposure time can be selected, regardless of the duration of the

[1]The use of an electronic shutter in the supericonoscope and superorthicon eliminates the harmful effect of photocathode thermal emission on the latent image.

readout from the memory. Selection of the optimum exposure time is based on a compromise between the desire to increase the exposure time and the necessity for decreasing this time, to decrease the shift of the optical image during the exposure. It is important for slow-scan system designers to estimate the gain which can be obtained by increasing exposure time in the transmitting camera. For such an estimate, the response characteristics of television storage devices must be studied and the connection of efficiency of use of the storage principle with these characteristics must be established.

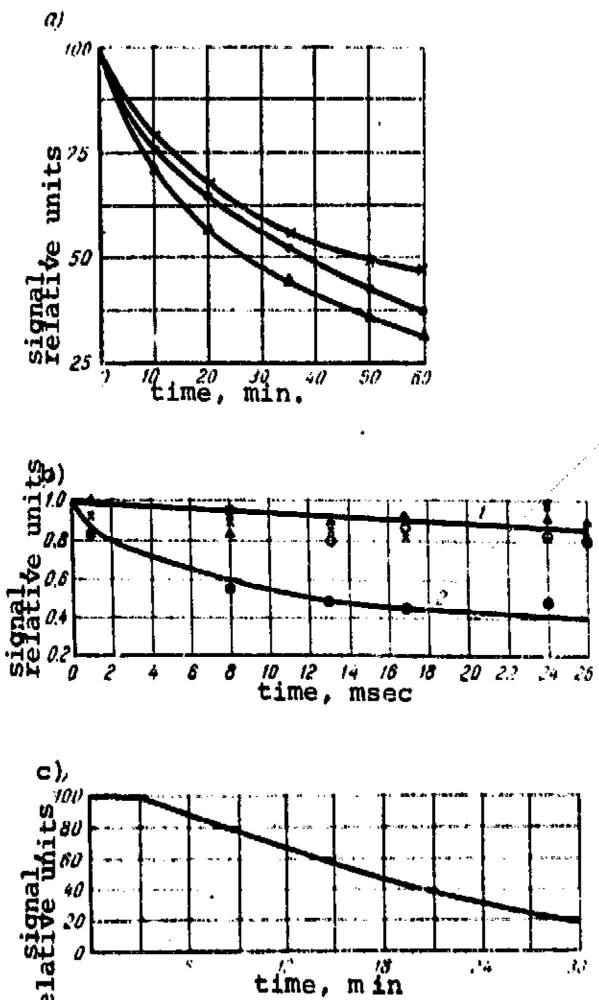


Fig. 3.4 Camera tube memory length characteristics; a) supericonoscope; b) superorthicon; c) slow-scan vidicon

Television storage devices have three types of time response [66, 72]: /131

-- Energy accumulation response;

-- Energy retention response, the memory;

-- Readout response.

The storage response characteristics, measured for standard types LI-13, LI-17 and LI-203 superorthicons, are presented in Figs. 3.5 and 3.6 [75]. These characteristics show the increase in signal-noise ratio, owing to the time increment of intensity ΔU of a latent image of test pattern 0249, in details of different sizes ℓ, with varying illumination B of the pattern image on the photocathode. Each family of characteristics reflects the function $\Delta U = \varphi(l, B)|_{l=\mathrm{const}}$.

The difference in the storage response characteristics and the memory characteristics represented in Fig. 3.4 flows from a comparison of them. The storage response is determined by the illumination B and, depending on the value of it, it can change within broad limits. The storage device memory length does not depend on illumination. /132

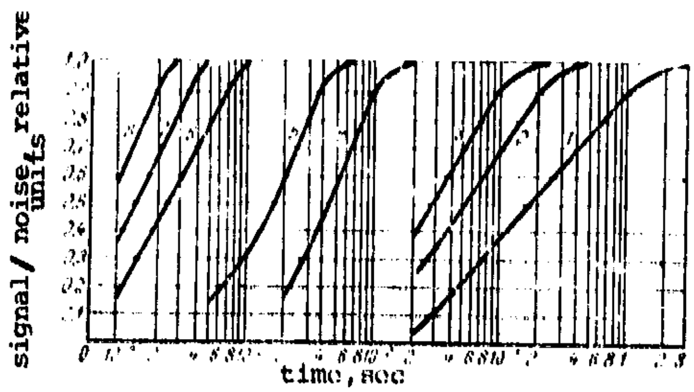


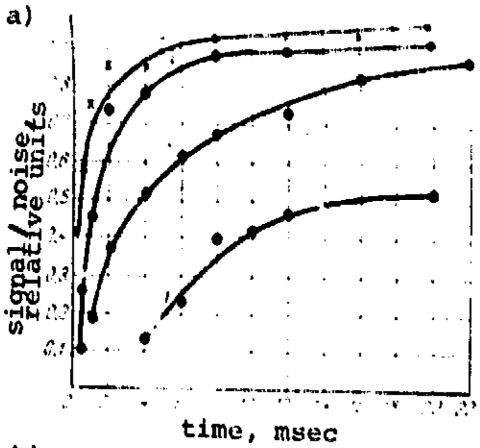
Fig. 3.5 Superorthicon storage characteristics for large detail with differing illumination B of the photocathode:

1 – $5 \cdot 10^{-4}$ lux; 2 – 10^{-3} lux; 3 – 10^{-2} lux; 4 – $5 \cdot 10^{-2}$ lux

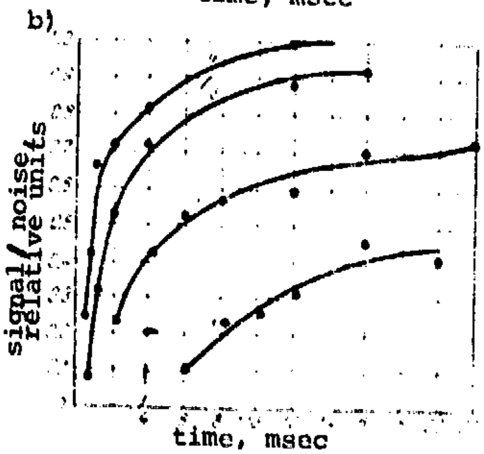
Analysis of the storage and memory response characteristics, reflecting the storage device properties, permits a simplified modeling system of one-band storage of a television film storage device to be synthesized (Fig. 3.7). The modeling system is a quadrupole, with two switching parameters, which are constant over time:

$$u_1(t) = \frac{CR_n(B)R_1}{R_n(B)+R_1} \cdot u_0 \quad Cl$$

a)



b)



c)

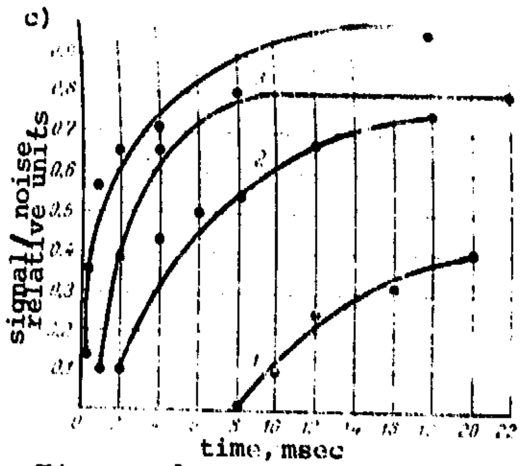


Fig. 3.6 Superorthicon storage characteristics for small details, with differing illumination B of photocathode, for small detail, corresponding to the vertical wedge of test pattern 0249 marker:
a) 300 lines; b) 400 lines;
c) 500 lines; 1. B=0.073 lux; 2. B=0.24 lux; 3. B=0.24 lux; 4. B=2.2 lux.

The key closes in storage time $0 \leq t \leq T_e$.

The storage and memory responses of a film storage device is described by the time characteristic of the modeling system:

$$H(t) = \begin{cases} 1 - e^{-\frac{t}{\tau_1(B)}} & \text{at } 0 \leq t \leq T_e \\ e^{-\frac{t-T_e}{\tau_2}} & \text{at } t > T_e \end{cases}$$

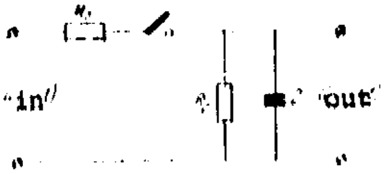


Fig. 3.7 Diagram modeling storage device unit band

With increase in illumination B, the time constant $\tau_1(B)$ decreases. The Duhamel integral applied to the modeling system has the form /134

$$u_{out}(t) = \int_0^t u_{in}(x) H'(t-x)\,dx, \qquad (3.2)$$

where $U_{in}(x) = m(x) + n(x)$ is the value of the input function: signal + noise.

In the partial case, with satisfaction of the conditions $\tau_1(B) > T_e$ and $\tau_2 \gg (t - T_e)$, the time characteristic

$$H(t) = \begin{cases} \dfrac{t}{\tau_1(B)} & \text{at } 0 \ll t \ll T_e, \\ 1 & \text{at } t > T_e. \end{cases}$$

In this case, formula (3.2) is transformed into the well-known formula [38]

$$u_{out}(t) = \frac{1}{\tau_1(B)} \int_0^t [m(x) + n(x)]\,dx.$$

The Fig. 3.7 modeling diagram permits a visual explanation of the effect of a finite memory length (time constant τ_2) on storage response (time constant $\tau_1(B)$) and possible differences in their values. The principal features in this problem consist of the following.

The presence of a specific memory is a necessary condition for accomplishing the storage process. In fact, the storage response time constant

$$\tau_1(B) = \frac{1}{\dfrac{1}{\tau_0(B)} + \dfrac{1}{\tau_2}}, \qquad (3.3)$$

where $\tau_0(B) = CR_0(B)$.

It follows from formula (3.3) that, in the absence of a memory ($\tau_2 = 0$), the storage response time constant equals zero.

The memory length and, consequently, the extent of gain in signal-noise ratio, as a function of storage process, is not determined unambiguously by storage response. In fact, at a given memory constant τ_2, the storage response constant $\tau_1(B)$ can take any value from 0 to τ_2, depending on illumination B. Memory length τ_2 unambiguously determines only the greatest value of the storage response constant, i.e., lim $\tau_1(B) = \tau_2$ as $B \to 0$. The situation presented above of the effect of memory on the storage process permits the expected gain from use of one type of storage device or another under various operating conditions to be correctly estimated.[1] /135

In application to the task of designing slow-scan systems, an important practical conclusion should follow from what has been said above, that, for each type of camera tube, there is a limiting value of the exposure time T_{ekr}, exceeding which should be accompanied by appreciable departure from the rule of interchangeability of the quantities B and T_e. The rule of interchangeability[2] states that, in preserving exposure value BT_e, exchange of quantity B for T_e should not lead to a decrease in the video signal. We satisfy the rule of interchangeability in any range of values of T_e, only with an infinitely large memory. /136

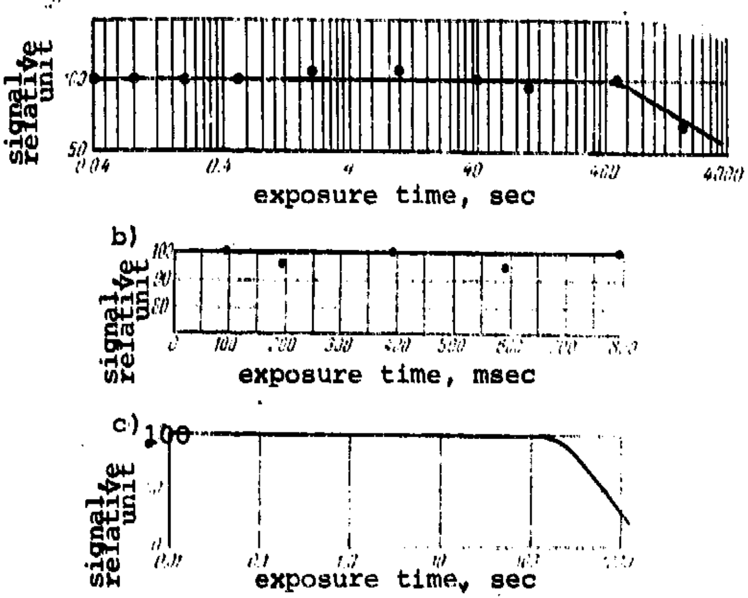


Fig. 3.8 Testing the rule of interchangeability for camera tubes: a) supericonoscope; b) superorthicon; c) vidicon

For television devices with the memory characteristics represented in Fig. 3.4, a noticeable decrease in video signal should be observed with increase in $T_e > T_{ekr}$, even with retention of constant exposure BT_e. The reason for this is a decrease in memory characteristics of the storage device.

The results of a test of the rule of interchangeability are presented in Fig. 3.8, for various types of transmitting tubes. The characteristics show a decrease in video signal with increase in exposure time T_e, under conditions of

[1]As an example, the estimate of the storage properties of a luminophore with prolonged persistence can be pointed out [10]. The presence of long persistence (long memory) in a luminophore still does not determine its storage persistence, which, depending on the excitation current value, can assume different values. The capacity of increasing the initial signal-noise ratio in one and the same luminophore with long persistence can be small by use of a luminophore, for example, in receiving devices operating with large excitation currents or, on the other hand, high in use of a luminophore with multicascade electron-optical converters operating with small excitation currents.

[2]The term is derived from photographic technology.

constant exposure BT_e. A decrease in the characteristics is observed, beginning with a time value exceeding the memory length. Knowledge of the limits of fulfillment of the rule of interchangeability permits selection of slow-scan system exposure times in an optimum manner.

3.3 Features of Formation of a Slow-Scan Video Signal

Availability of film storage devices, capable of storing with the optimum exposure and retaining the stored image for a long period of time, permits selective transmission of television images which differ significantly from each other in semantic content. It is natural that this image selection process, significantly weakening the semantic correlation between neighboring frames, completely eliminates the statistical correlation between frames. Complete elimination of the interframe statistical excess should lead to equalization of the video signal spectrum (see section 1.5) and, consequently, to a more nearly optimum statistical matching of the video signal sensor with the channel. In this respect, the slow-scan method can belong to statistical methods of video signal spectrum compression.

Complete elimination of the interframe statistical excess in the slow-scan method means elimination of the principal fraction of the statistical excess in television images. Use of intraframe excess in the slow-scan method gives only a small addition to the video signal spectrum compression which can be achieved, but it requires complicated apparatus. Therefore, the readout process in slow-scan systems is carried out by the traditional television method of scanning at a constant rate.

As is well-known, the video signal spectrum generated by the transmitting camera depends on the readout rate (or on the readout time interval at a constant readout rate).

In carrying out course photography by means of the slow-scan system (Fig. 3.1), the following are selected to achieve a given resolution:

Exposure time $T_e \quad \frac{1}{2\nu_s v_0}$ sec,

frame transmission time /137

$$T_f \quad \frac{l_\phi(1-p_x)}{v_0}, \qquad (3.4)$$

where v_e is the rate of movement of optical image across a photo layer of size ℓ_ϕ and p_x is the longitudinal frame overlap: $p_x \ll 1$.

The excess of the frame transmission time over exposure time

$$\eta = \frac{T_{\kappa}}{t_0} = 2\nu_x l_\phi (1-\rho_x). \qquad (3.5)$$

If course photography were carried out by a broadcast type television system (with simultaneous storage and readout processes), the frame transmission time would be equal to the exposure time. Therefore, formula (3.5) gives an estimate of the increase in frame transmission time in the slow-scan method or an estimate of image transmission frequency band compression. This formula shows that the gain η in frequency band compression in the slow-scan method is greater, when transmission of images of moving objects is required with high resolution. This gain can reach values on the order of 1,000.

Thus, slow-scan method permits formation of a video signal from rapidly changing natural scenes in an η times more narrow band than that of a broadcast television signal, while preserving the identical resolution. This provides for solution of the problem of increasing television transmission range from spacecraft.

Solution of the problem of increasing light sensitivity and resolution involves creation of the optimum television camera (section 2.6). Such difficulties stand in the way of creating the optimum camera as limitation of the working exposure range, because of saturation of the light characteristics and the presence of sources of inherent noise of the camera circuits, in addition to photon noise.

Extension of the linear section of the light curve is achieved by increasing the charge which a transmitting tube target is capable of storing. For this, the capacitance of the storing target or the difference in limiting potential levels must be increased. Construction of camera tubes storing very high charges in a broadcast television system is extremely difficult, since such tubes will have unacceptably high persistence. Broadcast television technology, having enriched television by the signal storage principle, restricts the frame of reference of its use. The slow-scan method, divided into storage and readout time processes, from its incorporation of special camera tube target erasure and preparation operations, which are effective means of control of tube persistence. The slow-scan method thereby opens the way to storage of very large charges on television tube targets. /138

Another way of extending the working exposure range consists of special processing of the stored, charged image, using subtraction of the potentials on the storage target (see sections 1.3 and 3.8).

The sources of inherent noise of the camera circuits can be taken into account, by means of the concept of the receiver noise factor.

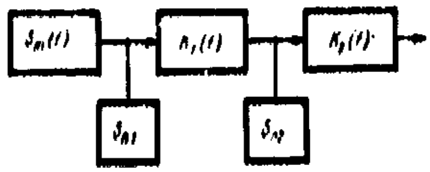


Fig. 3.9 Explanation of noise factor calculation

We turn to the diagram in Fig. 3.9. A message, mixed with white noise S_{n1}, enters the input of a receiver, containing filters $K_1(f)$ and $K_2(f)$, separate sources of inherent white noise S_{n2}. The noise power at the output

$$P_{n\Sigma} = P_{n1} + P_{n2} = \int_0^\infty S_{n1} K_1^2(f) K_2^2(f)\, df + \int_0^\infty S_{n2} K_2^2(f)\, df.$$

The receiver noise factor

$$W = \frac{P_{n1} + P_{n2}}{P_{n1}} = 1 + \frac{b_0 S_{n2}}{S_{n1} K_1^2(0)}, \tag{3.6}$$

where

$$b_0 = \frac{\int_0^\infty K_2^2(f)\, df}{\int_0^\infty \frac{K_1^2(f)}{K_1^2(0)} K_2^2(f)\, df}.$$

The noise factor involves calculation of the peak output signal-noise ratio. If the peak signal power at the output is P_s, it is clear that $W = 1 + q_1^2/q_2^2$, where $q_1^2 = P_s/P_{n1}$, $q_2^2 = P_s/P_{n2}$. Knowing q_1 and W, it is easy to find the total signal-noise ratio at the output:

$$q_{1,2} = \sqrt{\frac{P_s}{P_{n1} + P_{n2}}} = \sqrt{\frac{q_1^2 q_2^2}{q_1^2 + q_2^2}} = \frac{q_1}{\sqrt{W}}. \tag{3.7}$$

Formula (3.6) permits, not only calculation of the noise factor, but it indicates a general method of reduction of the noise factor, which consists of incorporation of amplification $K_1(0) > 1$ between the sources of the input and inherent noises.[1] To reduce the noise factor to two, an amplifier must be installed between the noise sources, /139 which would amplify the mixture of the input message and noise, with gain:

$$K_1(0) = \sqrt{\frac{b_0 S_{n2}}{S_{n1}}}.$$

Among the inherent noises of the television camera circuits, we distinguish the shot noise of the video signal current and the video amplifier noise. The output power of the video signal current shot noise I_c, which can be found by measuring the light characteristics

---

[1]An alternative to this method of reduction of the noise factor may be the method of coding the message and noise mixture [41].

by the Schottky formula

$$P_s = 2eI_s \int_0^\infty K_a^2(f)\,df = 2eI_sF_e,$$

where $K_a(f)$ is the amplitude-frequency characteristic of a video amplifier with equivalent frequency band F_e. In amplification of the video signal, the inherent noise of the video preamplifier, with power P_{na}, is added. These inherent noises can be taken into account by means of:

(a) C a m e r a tube noise factor

$$W_{tt} = \frac{P_{n\phi} + P_{ns}}{P_{n\phi}},$$

where $P_{n\phi}$ is the photon noise power at the tube output;

(b) Video preamplifier noise factor

$$W_a = \frac{P_{ns} + P_{na}}{P_{ns}}.$$

The ratio of the video signal amplitude to photon noise (see formula 1.3)

$$a_\phi = \gamma k \Delta t \sqrt{aB_\phi T}.$$

The ratio of the video signal current amplitude from a large detail of maximum contrast to its shot noise

$$a_s = \sqrt{\frac{P_s}{P_{ns}}} = \frac{I_s}{\sqrt{2eI_sF_e}} = \sqrt{\frac{\Delta Q}{e}}, \qquad (3.8)$$

where $$\Delta Q = \frac{I_s}{2F_e}.$$

An increase in charge ΔQ, stored by a unit band of the storage target, means that the tube creates a large video signal current in a single frequency band I_s/F_e.

The resulting signal-noise ratio, which is determined by the photon noise and the video signal current, in accordance with formula (3.7)

$$a_{\phi s} = \frac{a_\phi}{\sqrt{W_{tt}}},$$

where $W_{tt} > 1$.

Reduction in the tube noise factor is achieved in secon type tubes by amplifying the electronic image before its readout, in accordance with the recommendations flowing from formula (3.6). Similarly, for reduction of the video preamplifier noise factor, an amplifier /140 (SEA), located between the sources of the video signal current shot noise and the video preamplifier inherent noise, is used. In superorthicon and vidicon type television tubes, with a return electron beam, the use of a secondary electron amplifier (SEA) in the readout section provides a ratio of the signal to the shot noise (large detail of maximum contrast)

$$q_{SEA} = \frac{I_s}{\sqrt{2e\frac{I_s}{m_1}F_e W_{SEA}}} = \sqrt{\frac{I_s}{2eF_e\frac{W_{SEA}}{m_1}}},$$

where m_1 is the depth of moderation of the return electron beam and W_{SEA} is the secondary electron amplifier noise factor.

For the superorthicon, $m_1 \sim 1/3$ and $W_{SEA} \sim 3$, i.e., $W_{SEA}/m_1 \sim 9$. Removal of the video signal from the signal plate of a vidicon provides a ratio of the signal to the video signal current and video amplifier noises

$$q_{sa} = \sqrt{\frac{q_s^2 q_a^2}{q_s^2 + q_a^2}} \approx \frac{I_s}{\sqrt{2eI_sF_eW_a}} = \sqrt{\frac{I_s}{2eF_eW_a}}. \qquad (3.9)$$

There are two possible reasons for the possibility of reducing noise factor W_a [74 - 76]:

(a) By reduction in the video amplifier noise power, with compression of the equivalent video frequency band, more rapidly than reduction of the video signal current shot noise power;

(b) By matching the internal resistance of the camera tube to the load resistance by reduction in the scan rate.

Let us dwell more in detail on this question.

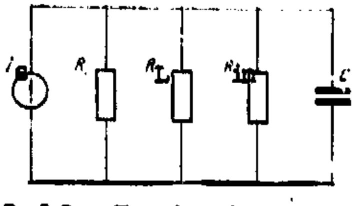


Fig. 3.10 Equivalent diagram of camera video amplifier input

Resistor R_L, shunting the spurious capacitance of the video preamplifier input, serves as the load for the video signal current created by the vidicon (Fig. 3.10). It is well-known from electrical technology that the current flow to the generator with internal resistance R_i on resistance $R_L = R_i$ provides the maximum generator power output. Satisfaction of this equality requires the internal resistance of the vidicon to be taken into account.

The value of the camera tube internal resistance in the memory readout mode is approximately $R_i = U_t/I_s$, in which

$$I_s = \frac{\Delta Q}{\Delta t} = \frac{U_T \Delta C_T}{\Delta t} = \frac{U_T C_T \Delta l^2}{l_0^2 \Delta t},$$

where I_s is the video signal current amplitude, Δt is the readout time of one element, C_T is the total capacitance of the target, $\Delta\ell^2$ is the area of the active section of the readout spot on the target and ℓ_ϕ^2 is the target area. /141

After designating the capacitance, which can be changed over by the readout beam in a unit of time $C_1 = C_t \Delta\ell^2/\ell_\phi^2 \Delta t$, we obtain $I_s = C_1 U_T$. Then, the internal resistance of the camera tube

$$R_i = 1/C_1. \tag{3.10}$$

At $C_T = 2 \cdot 10^{-9}$F, the equivalent transmission frequency band $F_e = 1/2\Delta t = 12.5$ kHz, $\Delta\ell^2/\ell_\phi^2 = 2.5 \cdot 10^5$, the internal resistance of the tube $R_i = 5 \cdot 10^9$ ohm. Formula (3.10) shows that the internal resistance of the tube depends on:

-- Target capacitance, the greater the target capacitance, the less the internal resistance;

-- Readout rate, the higher the readout rate, the less the internal resistance;

-- The size of the active section of the readout spot, the larger the active section, the less the internal resistance.

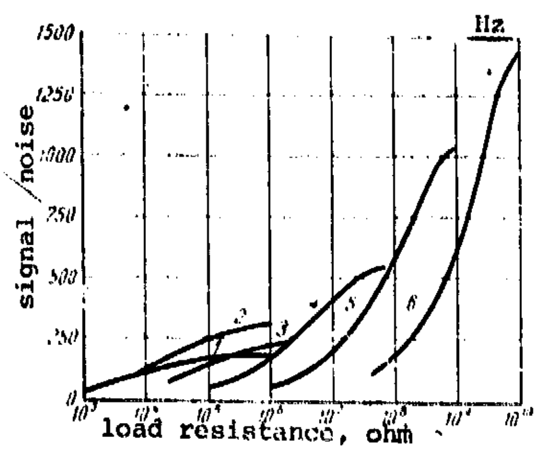


Fig. 3.11 Calculated values of peak signal-noise ratio of slow-scan camera video amplifier, at $C = 2.10^{-11}$F and various values F_e: 1, 2 – $6.5 \cdot 10^4$ Hz, 3 – 10^5 Hz, 4 – 10^4 Hz, 6 – 10^3 Hz, 5 – 10 Hz.

Selection of load resistance R_L in a broadcast television system usually does not take the internal resistance of the tube into consideration [17]. This does not lead to error, because the readout rate of the charges from the target of a tube of a given type in a broadcasting system is constant. In slow-scan television, the readout rate (or time) is a selected value. Therefore, it is necessary to take change in the internal resistance of the tube with change in memory readout time into consideration, in selecting the load resistance. Calculated data of the effect of increase in load resistance in proportion to compression of the video frequency band on the signal-noise ratio q_{sa} of the video preamplifier is given in Fig. 3.11 [75]. Curve 1 of Fig. 3.11 concerns a tube with 300 ohm noise resistance and curve 2 to a tube with 1,000 ohm resistance. In the calculation, the increase in noise resistance of the input tube in suppression of the video frequency band is taken into account.

The calculated data in the region of high signal-noise ratios was /142 confirmed experimentally in a slow-scan camera, with a video preamplifier having a tube input [75]. The camera operated with a LI-408 slow-scan vidicon, the light characteristics of which, at an exposure of 7 lux·sec, provided a video signal current $I_s = 5 \cdot 10^{-9}$ A at 500 lines and a $1.25 \cdot 10^4$ Hz video frequency band (divided storage and readout time mode). The video signal voltage at the video preamplifier input at the line frequency was 1.1 V, at $R_L = 10^8$ ohm. A large ratio of the signal to the video amplifier noise $q_a = 1400$ and to the video signal current noise $q_s = 1120$, was achieved. The resulting output signal-noise ratio (see formula (3.9)) was 800. Such a high signal-noise ratio was unknown in broadcast television technology.

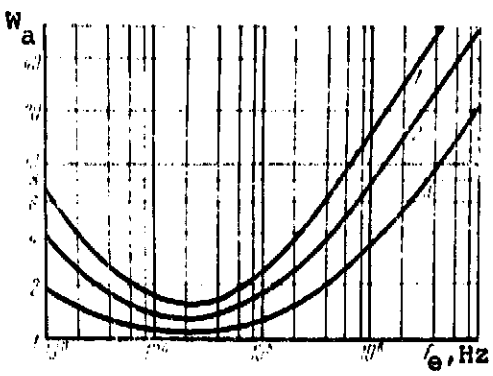


Fig. 3.12 Video amplifier noise factor vs. equivalent frequency band: 1) for vidicon with ratio $I_s/F_e = 10^{-14}$ A/Hz; 2) $I_s/F_e = 4 \cdot 10^{-14}$ A/Hz; 3) $I_s/F_e = 6 \cdot 10^{-14}$ A/Hz.

Calculated data on the dependence of a semiconductor video amplifier noise factor (see section 3.7) on its equivalent video frequency band are presented in Fig. 3.12. The calculation was carried out, with allowance for increase in load resistance with decrease in equivalent video frequency band F_e. The calculated curves have the ratio I_s/F_e as a parameter, which determines, together with the noise factor, the output signal-noise ratio (formula 3.9). Calculated W_a vs. F_e curves have a minimum $W_{a\,min}$, the value of which decreases for vidicons creating a large current in a single band I_s/F_e. These curves permit determination of the range of values of F_e, on which the use of vidicons with SEA in the readout section, providing for achievement of a ratio $W_{SEA}/m_1 < W_a$, is based. The abscissa of the intersection point of the calculated curve with the noise factor $W_a = W_{SEA}/m_1$ divides the values of F_e into two ranges: At large values of F_e, use of SEA is advisable, but at low values of F_e, in taking the video signal from the vidicon signal plate and using a semiconductor video preamplifier, the best results should be expected. Especially promising for slow-scan television is the /143 range of values of F_e, in which the noise factor W_a is less than 2. It is clear from Fig. 3.12 that, for vidicons with $I_s/F_e = 10^{-14}$ A/Hz, $W_a < 2$ is reached in the 6 kHz $\leq F_e \leq$ 80kHz range. An increase in current in a single band to a value of $I_s/F_e = 6 \cdot 10^{-14}$ A/Hz extends the range to 1 kHz $\leq F_e \leq$ 0.4 MHz.

The conclusion of the possibility of reduction of the noise factor of a semiconductor video preamplifier below 2 was tested experimentally in a slow-scan camera [76]. The camera operated with type LI-408 vidicon, generating a $2 \cdot 10^{-9}$ A video signal from a large detail, with a target exposure of 3 lux·sec and 1,000 lines. A semiconductor video amplifier was used in the camera, which, according to calculations (curve 2, Fig. 3.12), had a noise factor $W_a = 1.8$ at $F_e = 0.1$ MHz. Oscillograms of the vidicon video signal were recorded on the screen of a type S1-29 oscilloscope, in the form of rectangular pulses, from the black-white illumination change.

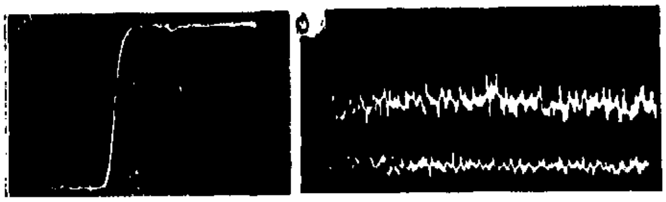


Fig. 3.13 Oscillograms of video signal from black-white brightness change: a) oscillogram of video pulse front; b) noise at "white" (above) and "black" (below) levels

An oscillogram of a video pulse front is given in Fig. 3.13a and, in Fig. 3.13b, its top (from white) and bottom sections (from black), separately, in order to better show the change in effective noise value. It is evident that the effective noise value at the white level (i.e., with the total noise of the video signal currents and video amplifier) is 1.5 times the effective value of the noise at the black level (i.e., video amplifier noise, together with the vidicon dark current noise). It is easy to find an experimental value of the noise factor from this, which matches well with the calculated value $W_a = 1.8$. The matching not only confirms the correctness of the calculation, but it shows that a video signal taken from the vidicon signal plate is masked, not by the readout beam current shot noise, but by the video signal current shot noise. This circumstance is of great importance for improving the qualitative characteristics of the camera, since the vidicon readout beam current can be several times greater than the video signal current.

At the present time, we attain a low noise factor $W_a \leq 2$, only /144
in slow-scan rate television with a relatively narrow video frequency band ($F_e \leq 0.4$ MHz). Achieving such a noise factor in a wider frequency band ($F_e > 0.4$ MHz) involves the need for perfecting field-effect transistors or using devices for cooling the input. Thus, slow-scan television provides for formation of a video signal with a better signal-noise ratio at the vidicon camera output, because of:

-- The use of thinner film storage devices, permitting accumulation of higher charge ΔQ, i.e., of creating larger video signal currents in a single band I_s/F_e. The residual charged image inherent in such tubes is not an uncorrectable deficiency in slow-scan television, since a forced erasure operation is provided for in the tube operating cycle;

-- Reduction of the noise factor of the video preamplifier, by means of matching the internal resistance of the vidicon to the low resistance in a narrow video frequency band.

As was shown in Chap. 2, an increase in the signal-noise ratio should provide an improvement in resolution of slow-scan vidicon cameras. Extension of the spatial amplitude-frequency characteristics of camera tubes, by means of decrease in the surface spread of charges, using thin film storage devices, and by means of improvement in focusing the electron readout beam, which is possible, owing to a decrease in beam current in a slow memory readout, also facilitates successful solution of the problem of increasing resolution in slow-scan television [74]. Of no less importance is the absence in the radio channel regulation GOST 7845-55 of the dispersion of image and audio carrier signals, which limits the increase in resolution in a broadcast television system. In slow-scan television, the amplitude-frequency characteristics of the video amplifier and radio channel can be selected from the conditions of transmission of all of the information directional video frequency bands generated by the camera tube.

In analyzing the results of measurement of directional amplitude-frequency characteristics of various transmitting tubes (together with the lens), it is easy to note their features: The curves do not have zero, i.e., there are no frequencies, at which the values of the characteristic equals zero. Based on the concept of a complete, one-time readout of charges stored on the target by an electron beam, this experimental fact is evidence that the operating (active) part of the readout spot decreases in proportion to the line width in the globe, by means of which measurement of the amplitude-frequency characteristics is carried out. The absence of zeros in the amplitude-frequency characteristics of vidicons was taken into consideration, in selection of approximating function (2.50), which was used for obtaining formula (2.94), for calculating the potential resolution. /145

Formula (2.94) can be made more specific in calculation of the signal-noise ratio for vidicon cameras, with expression (3.9) taken into consideration. For this, we transform formula (3.9), by means of the relationships:

$$F_{t} = b v_{ro} \nu_{z} = \frac{b z^{2}}{2 T_{ro}}, \qquad (3.11)$$

$$z = 2 \nu_{z} l_{\Phi}, \qquad (3.12)$$

$$\rho = \frac{I_{s} t_{ro}}{l_{\Phi}^{2}}, \qquad (3.13)$$

where b is a numerical coefficient (see section 2.5), v_{ro} and T_{ro} are the readout rate and time, $2\nu_{z} = z/\ell_{\Phi}$ is the line density, ρ is the density of the stored electrons forming the video signal. After transformation, we obtain formula (3.9), in the form

$$q_{sa} = \frac{1}{2\nu_{z}} \sqrt{\frac{\rho}{b W_{a}}}. \qquad (3.14)$$

The signal-noise ratio from a low-contrast large detail, by definition (formula 2.86)

$$q_{\Delta} = k \gamma q_{sa} = \frac{k \gamma}{2 \nu_{z}} \sqrt{\frac{\rho}{b W_{a}}}. \qquad (3.15)$$

The value of the vidicon video signal current can be represented by the formula (see section 1.3)

$$I_s = \varepsilon \eta_s e a B l_\phi^2 \frac{T_e}{t_0}, \tag{3.16}$$

where ε is the quantum yield of the internal photoeffect; η_s is the coefficient of efficiency of formation of the video signal current. We note that the signal-noise ratio (3.15), obtained in removal of the video signal from the vidicon signal plate, is connected with the photon signal-noise ratio q_ϕ by the expression

$$q_s = \sqrt{\frac{\varepsilon \eta_s}{b W_a}}\, q_\phi = \sqrt{\frac{\varepsilon \eta_s}{b W_a}}\, \gamma k \sqrt{a B_\phi T_e} \, l^2. \tag{3.17}$$

By substituting (3.15) in formula (2.94), we can calculate the potential resolution along a line, for the vidicon camera

$$\nu_{Sx} = \nu_{0,5} \left(\frac{k \gamma}{2 \nu_z q_{thr}} \sqrt{\frac{\rho}{b W_s}} \right)^{\frac{1}{\alpha}}. \tag{3.18}$$

Calculation of the potential resolution of slow-scan vidicon cameras by formula (3.18) permitted the prediction of values, exceeding resolutions known in broadcast television. This prognosis was tested experimentally. The test was carried out by multiline globes of maximum contrast, on which it is easiest of all to carry out photometry. /146

The results of measurement of the frequency signal-noise ratio of a slow-scan vidicon camera at various exposures are presented in Fig. 3.14. The directional amplitude-frequency characteristic of a type LI-408 slow-scan vidicon (curve 1), measured together with a Industar-50 lens, is presented in Fig. 3.15a Curve 2 is the characteristic of the Industar-50 lens, from the data of work [77]. The slow-scan camera on which the measurements were carried out had a semiconductor video preamplifier (see section 3.7), with a flat amplitude-frequency characteristic in the information video frequency band ν_{Sx}. A ν_{Sx} = 135 per./mm resolution along a line (or at ℓ_ϕ = 11mm, we have $2\nu_{Sx}\ell_\phi$ = 2970 elements per line) was achieved with an exposure of 3 lux·sec, with number of lines z = 1,000 and an output signal-noise ratio q_{sa} = 200 [78]. The symmetrical potential resolution responded to z_S = 2,000 lines and 2 $\nu_S \ell_\phi$ 2,000 elements per line on a photo layer, 11 X 11 mm in size, with a signal-noise ratio of 60. /147

Such a high resolution has been unknown in broadcast television technology. However, the figures presented are not limiting. It is evident from the curve of Fig. 3.15a that the Industar-50 lens greatly limited the high resolution achieved. With improvement in lens or without a lens (as in holography), higher resolution can be expected of slow-scan cameras. The principal factors limiting resolution of slow-scan vidicon cameras at the present time are the directional amplitude-frequency characteristics of the electron optics of the vidicon and the video signal current noise. Solution of the problem of increasing resolution of the camera is of great importance, not only in the interest of improving television image quality or of introducing holographic principles, but for building cameras of minimum sizes. The dimensions of the human eye can serve as an example. Minimum dimensions extend the possibilities of inclusion of television cameras in the onboard apparatus. Moreover, decreasing the camera dimensions will develop new prospects for solution of the problems of efficient scanning of large areas by the camera field of view, similar to the scanning accomplished by the human eye in searching for a needed object in a large field.

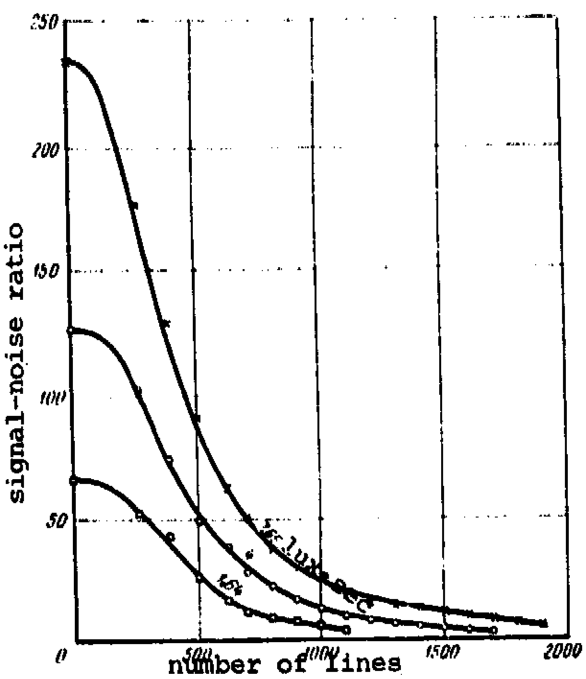


Fig. 3.14 Frequency signal-noise ratio of slow-scan vidicon camera measured oscillographically by means of multiline globe

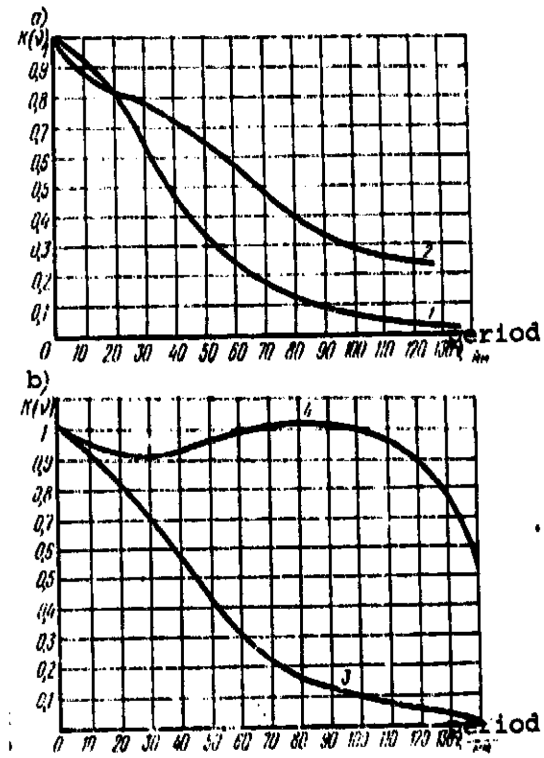


Fig. 3.15 Amplitude-frequency characteristics of vidicons: a) 1. type LI-408 slow-scan vidicon with Industar-50 lens; 2. Industar-50 lens; b) 3. Slow-scan vidicon with return beam, from data of work [79]; 4. lens

In photography, coverage of large areas is accomplished by means of a camera, having photographic film 190 mm and 320 mm wide [35]. The area of the light-sensitive layer in vacuum television camera tubes is significantly less than that of the photographic film. A trivial way of increasing the light-sensitive area is construction/148 of multitube television cameras. However, this way is restricted by permissible increase in dimensions, weight and energy consumption of the onboard apparatus. Therefore, the possibility of accomplishing scanning with the field of view of a single-tube camera with large fields of view is attracting attention. The simplest example of a system, in which such scanning is accomplished, is a slow-scan camera with mechanical, sectional scanning of the observed field with a mirror installed in front of the camera. A television tube operating cycle time must be selected for this, M times less than the time of change of subject in the camera field of view and, correspondingly, acceleration of the readout process, i.e., extending the video signal spectrum. We explain this by the example of a system, intended for transmission of images of the surface of some planet. If the camera tube operating cycle length is made M times less than the transit time of the camera from position 1 to position 2 (see Fig. 3.1), the camera can transmit M television frames, formed by scanning the field of view across the direction of its motion, in the transit time. Scanning of the instantaneous field of view of the camera can be accomplished, for example, by rocking a mirror, similar to the way in which it is done in a mechanical system (see sections 1.3 and 4.2). The mirror can be transferred from one position to the other during the time of videoinformation readout from the memory in the camera tube. Expansion of the field of view of a slow-scan camera by M times is achieved by this method, and it is accompanied by a M-fold extension of the video signal spectrum. Such a slow-scan method of transmission is called sectional.

Not only is transmission of a television image by sections of great importance, but their reproduction, in slow-scan systems. As a rule, the final result of a slow-scan system is television photos from the picture tube screen, which undergo detailed study. However, the process of reproduction of a television frame in a single picture tube involves considerable loss of videoinformation, which is caused by a decrease in contrast with increase in directional frequency. For comparison, the frequency characteristics of the contrast in a modern 47LK1B-S picture tube and 35-mm photographic film are presented in Fig. 3.16. The quantity $2\nu\ell$, line/line, where ℓ is the line length (the line length is taken as 24 mm for KN-1 motion picture film), is plotted on the abscissa. It is evident from the figure that strong frequency distortions of the picture tube cause considerable losses of videoinformation in reproduction of television images, with a number of elements in a frame of over 10^6. To decrease losses of videoinformation, i.e., to decrease the drop in contrast of high directional frequencies, is possible by reproduction of a television frame, for example, on four picture tubes. With this sectional method of image reproduction, photographs of a television frame are assembled from four photographs, obtained by photographing the screen of each picture tube.

The resolution values of a slow-scan vidicon camera were /149
measured with multiline globes, using a video preamplifier having a flat amplitude-frequency curve in the information frequency band.

In television practice, the so-called aperture correction is used in a video amplifier, which creates a rise in the amplitude-frequency curve in the high frequency region. The aperture correction system, as the name itself states, is intended for correction of the drop in the directional amplitude-frequency curve of a camera tube (i.e., correction of the camera tube aperture). The favorable effect shown by incorporation of an aperture correction system for resolution of two lines was demonstrated in Fig. 2.18. Bringing into being the potential resolution determined by the two-line Foucault globe (see section 2.5), is accompanied by incorporation of an aperture correction unit in the camera video amplifier. Deviation in shape of the amplitude-frequency curve of the video amplifier from flat poses the problem of finding the optimum shape of the curve. To solve it, the concept of the optimum Viner filter can be used [28, 45]. As applied to a video amplifier, a Viner filter is specified in the following manner. The input video signal m(t) passes through filter $K_{tt}(f)$, which is equivalent in linear distortion to the camera tube. The distorted video signal from filter $K_{tt}(f)$ output, mixed with noise n(t), enters the input of filter-video amplifier $K_a(f)$. A requirement is placed on the video amplifier to amplify the video signal, with correction of the linear distortions of the camera tube. Therefore, the video amplifier must not simply reproduce function m(t) with minimum distortion, but reproduce the video signal in corrected form h(t), which is connected with m(t), by means of operator L: h(t) = L{m(t)}.

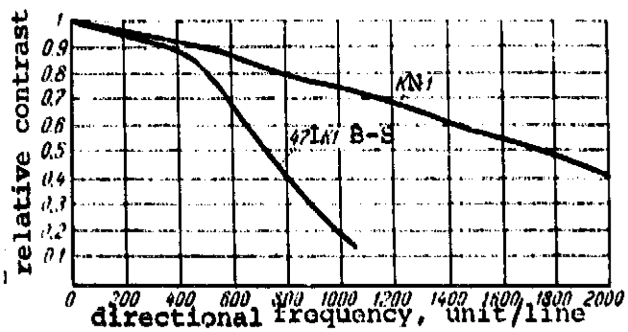


Fig. 3.16 Frequency characteristics of 47LK1B-S picture tube and KN-1 motion picture film

The spectral plane of the corrected video signal power /150

$$S_h(f) = S_m(f)|L(f)|^2 = S_{m0}(f)|K_{TT}(f)|^2|L(f)|^2, \quad (3.19)$$

where L(f) is the transmission function of the correcting operator.

Signal x(t) at the video amplifier output, with transmission function K(f), because of the linear distortions of the video amplifier and noise n(t), can represent the desired signal h(t), only with an error, the root mean value of which

$$\varepsilon^2 = \lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} [h(t) - x(t)]^2 dt. \quad (3.20)$$

We reproduce the optimum filtration of an optimum transmission function $K_{opt}(f)$ obtained in theory, minimizing root mean error

(3.20). If the condition of the physical feasibility of the filter is not taken into consideration and the absence of correlative connections between the signal and noise is assumed, this optimum transmission function can be expressed as [34]

$$K_{opt}(f) = \frac{L(f)\, S_m(f)}{S_m(f) + S_n(f)}, \tag{3.21}$$

In choosing a transmission function from formula (3.21), the root mean error in reproduction of h(t) reaches its minimum value [45]

$$\varepsilon^2_{min} = \int_{-\infty}^{\infty} \frac{|L(f)|^2\, S_m(f)\, S_n(f)}{S_m(f) + S_n(f)}\, df. \tag{3.22}$$

A video signal, with varying degrees of noise, which depends on the contrast of the observed object and the exposure value, enters the video amplifier input from the camera tube. Therefore, if the recommendations flowing from formula (3.21) are strictly followed, the optimum transmission function of the video amplifier should be automatically regulated, depending on the light conditions of observation of the object and the exposure time.

To engineer automatic regulation of the video amplifier amplitude-frequency characteristic under various light conditions, a control signal must be extracted. The use of the measured signal-noise ratio from a large detail has been proposed as the control signal in such an adaptive video amplifier [80]. For a given type of camera tube, the peak signal-noise ratio from a large detail determines the maximum amount of information R_S in a television frame (see formula (2.92)) and, therefore, its use as a control signal is justified.

Finding the transmission function of a filter, which is the reverse of filter $K_{tt}(f)$, by the iteration method [81], permits determination of the type of correcting operator: /151

$$L_n(f) = 1 + [1 - K_{TT}(f)] + [1 - K_{TT}(f)]^2 + \dots + [1 - K_{TT}(f)]^n. \tag{3.23}$$

Sum (3.23), with an infinite increase in the number of its terms, tends towards the limit:

$$\lim_{n\to\infty} L_n(f) = \frac{1}{K_{TT}(f)}. \tag{3.24}$$

A value on the order of the highest exponent n of polynomial (3.23) can serve as an estimate of the possible degree of correction of linear distortions of the camera tube. Achievement of a high degree of correction is hindered by noise, rise in power of which at the video amplifier output, with a rise and extension of the amplitude-frequency characteristic, leads to an increase in the root mean error.

3.4 Television Camera Light Sensitivity

Light sensitivity is a measure which estimates the effect of light parameters (for example, decrease in illumination and background illumination) on the excess of the signal-noise ratio or the threshold value q_{thr} of the frequency signal-noise ratio. Two types of television cameras were defined in section 2.6: A camera quasi-matched with the simplest image and a suboptimum camera for receiving a complex image. In accordance with this, we discuss estimates of light sensitivity.

A typical example of a quasi-matched camera is the television camera used in astronomy for recording stars (point sources of light) [83]. In this case, a scattering circle with effective area $\Delta\ell_1^2$ is projected by the telescope lens on a television camera photo layer. The light parameters are the illumination E created by the star (point source) in the plane of the telescope lens entry pupil and the background brightness B_ϕ, created by illumination of the night sky and extraneous illumination. Depending on the light sensitivity of the camera, light parameters E and B_ϕ provide a greater or lesser excess of the output signal-noise ratio $\bar{q}$ over the threshold q_{thr}.

We examine the dependence of the signal-noise ratio q on light parameters E and B_ϕ, initially without taking their spectral characteristics into consideration and then, allowing for their effect on choice of light filter.

The effective area of the camera tube target storage band $\Delta\ell_2^2$ can be found from its directional amplitude-frequency characteristics (AFC), considering that the directional AFC of the tube is isotropic: /152

$$\Delta l_2 = \frac{1}{\int_0^\infty K_T(\nu)\, d\nu}, \tag{3.26}$$

where $K_{TT}(\nu)$ is the AFC of the tube and ν is the directional frequency.

If the condition

$$\Delta l_1^2 \leqslant \Delta l_2^2, \tag{3.27}$$

is satisfied, it can be considered that all of the light flux from a point source enters one storage band. In this case, the value of this light flux

$$F = \frac{1}{4}\pi d^2 \tau E, \tag{3.28}$$

where E is the illumination created by a point source in the plane of the inlet pupil of the lens, d is the lens inlet aperture diameter and τ is the transmission coefficient of the lens.

The illumination created on the photocathode of the tube by a uniform background,

$$E_\Phi = \frac{\pi}{4}\tau B_\Phi \frac{d^2}{l_f^2}, \tag{3.29}$$

where B_Φ is the background brightness and l_f is the focal length of the lens.

The light flux from the background in the storage band

$$F_\Phi = \frac{\pi}{4}\tau B_\Phi \Delta l_2^2 \frac{d^2}{l^2}. \tag{3.30}$$

The average number of photons from a point source in the storage band in exposure time T

$$\Delta N = \frac{\pi}{4} a \tau d^2 E T, \tag{3.31}$$

where a is the number of photons in one lumen per second.

The average number of photons from the background during the exposure time in the storage band

$$\bar{N}_i = \frac{\pi}{4} a \tau \Delta l_2^2 B_\Phi T \frac{d^2}{l_f^2}. \tag{3.32}$$

Substituting the values of $\Delta\bar{N}$ and $\bar{N}_i$ from (3.31) and (3.32) in formula (1.3), we obtain an expression for the signal-noise ratio caused by photon fluctuations:

$$q = \frac{E}{\sqrt{B_\Phi}} l_f d \sqrt{\frac{\pi}{4}\frac{a\tau T}{\Delta l_2^2}}. \tag{3.33}$$

We allow for the quantum yield of the photocathode $\varepsilon \leq 1$ of actual tubes and the target noise factor. Considering that the gain of the target K_T is a random value having a Poisson distribution, it can be shown, by using a complex Poisson distribution [82], that the target noise factor /153

$$W_T = \frac{K_T + 1}{K_T}. \tag{3.34}$$

If the gain of the target K_T is sufficiently high, which occurs, for example, in a secon type tube, the readout beam shot noise can be disregarded, in comparison with the photoelectron noises.

Taking the effect of the photocathode quantum yield into consideration, for the case $K_T \gg 1$, formula (3.33) for the signal-noise ratio takes the form

$$q = \frac{E}{\sqrt{B_\Phi}} l_F \; d \sqrt{\frac{\pi}{4} \frac{a \varepsilon \tau T}{\Delta l_2^2}}. \qquad (3.35)$$

If condition (3.27) is not satisfied and the inequality

$$\Delta l_1^2 > \Delta l_2^2, \qquad (3.36)$$

takes place, this leads to a decrease in the light flux from the source falling on one charge storage band in the tube target, which is proportional to the area ratio $\Delta \ell_2^2 / \Delta \ell_1^2$, and an additional factor appears in expression (3.35) [83]

$$q = \frac{E}{\sqrt{B_\Phi}} l_F \; d \frac{\Delta l_2^2}{\Delta l_1^2} \sqrt{\frac{\pi}{4} \frac{a \varepsilon \tau T}{\Delta l_2^2}}. \qquad (3.37)$$

It is clear from Eqs. (3.35) and (3.37) that, for a point source, the signal-noise ratio increases in proportion to the product of the lens diamter and focal length. The signal-noise ratio is directly proportional to the square root of the background brightness. We turn to the dependence of the signal-noise ratio on storage band area. Signal, noise and signal-noise ratio vs. storage band area $\Delta \ell_2^2$ are shown in relative units in Fig. 3.17. As is clear from Fig. 3.17, the signal increases in proportion to storage band area until it is equal to the scattering circle area $\Delta \ell_1^2$. Background noise, the root mean value of which is proportional to the square root of the number of background photons, is independent of $\Delta \ell_1^2$, and it increases unrestrictedly with increase in storage band. A signal-noise ratio maximum occurs upon satisfaction of condition $\Delta \ell_1^2 = \Delta \ell_2^2$. /154

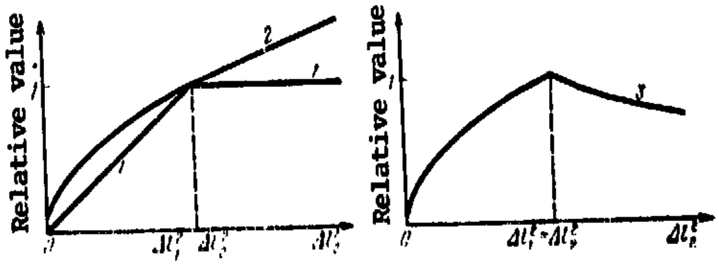


Fig. 3.17. Signal (1), noise (2) and signal-noise ratio (3) vs. storage band area

In detection of a point source of light on a uniform background, by a receiver with a threshold resolver, two types of error are possible because of statistical fluctuations: Taking a random noise overshoot as a signal (false alarm) and omission of a signal, because of a random decrease in signal level below the threshold.

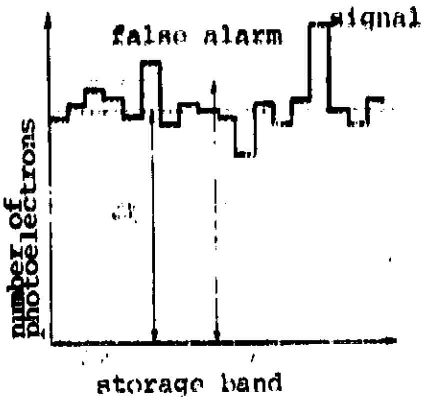


Fig. 3.18 Threshold level selection

It is clear from Fig. 3.18 that, with change in background brightness, to preserve a given probability of a false alarm, the threshold level C should change in proportion to the value of $\varepsilon\bar{N}_1$.

A more nearly correct determination of optimum shape and area of the storage band in the problem of detection of a light spot on a gray background requires finding the values of (3.31) and (3.32), with allowance for distribution of illumination in the spot E(x, y) and in the background $E_\phi(x, y)$ ahead of the lens:

$$\Delta \bar{N} = aT \iint_{(x,y)} \tau_{out}(x,y)\,dx\,dy \iint_{(x',y')} E(x', y')\,h(x-x', y-y')\,dx'\,dy'; \qquad (3.38)$$

$$\bar{N}_t = aT \iint_{(x,y)} \tau_{out}(x,y)\,dx\,dy \iint_{(x',y')} E_\phi(x', y')\,h(x-x', y-y')\,dx'\,dy', \qquad (3.39)$$

where h(x, y) is the directional pulse characteristic of the lens and $\tau_{out}(x, y)$ is the transmission factor of the mask on the photocathode.

We change the order of integration, and we designate the convolution and, taking the symmetry of the pulse characteristic of the lens into consideration:

$$\tau_{in}(x', y') = \int_0^\infty\int_0^\infty \tau_{out}(x, y)\,h(x'-x, y'-y)\,dx\,dy. \qquad (3.40)$$

T:en, the photon signal-noise ratio is determined by the functional from expression (3.40):

$$q = \frac{\Delta \bar{N}}{\sqrt{\bar{N}_t}} = aT \frac{\int_0^\infty\int_0^\infty E(x', y')\,\tau_{in}(x', y')\,dx'\,dy'}{\left[\int_0^\infty\int_0^\infty E_\phi(x', y')\,\tau_{in}(x', y')\,dx'\,dy'\right]^{\frac{1}{2}}}. \qquad (3.41)$$ /155

With symmetrical distribution of illumination, we can change to polar coordinates. Then, function (3.40) $0 \leq \tau_{in}(\rho) = \leq 1$, by maximizing functional (3.41), rectangular (equal to 0 or 1), and radius r of the storage band is determined by limitation of the differential contrast of the spot with the level, in accordance with the condition

$$\frac{E(\rho)}{E_\Phi(\rho)}\rho \leqslant r \; \frac{\int_0^\infty E(\rho) f_{nor}(\rho)\rho d\rho}{2\int_0^\infty E_\Phi(\rho) f_{nor}(\rho)\rho d\rho} = \frac{\int_0^r E(\rho)\rho d\rho}{2\int_0^r E_\Phi(\rho)\rho d\rho}, \qquad (3.42)$$

Let us examine the problem of maximization of a functional of type (3.41) in greater detail, with the example of the dependence of ratio (3.35) on wavelength. We take the spectral density of the background radiance $B_\phi(\lambda)$ and the spectral density of the radiation created by a point source in the plane of the inlet pupil of the lens $E(\lambda)$ into consideration [85, 86].

Then, formula (3.35) is reduced to the form

$$q = l_f \; d\sqrt{\frac{\pi T}{4h_0 C_0 \Delta l_2^2}} \; \frac{\int_0^\infty E(\lambda)\tau(\lambda)\varepsilon(\lambda)\lambda d\lambda}{\left[\int_0^\infty B_\Phi(\lambda)\tau(\lambda)\varepsilon(\lambda)\lambda d\lambda\right]^{\frac{1}{2}}}, \qquad (3.43)$$

where $h_0 = 6.62 \cdot 10^{-34}$ Watt$\cdot$sec^2 is Planck's constant, $C_0 = 3 \cdot 10^8$ m/sec is the speed of light in a vacuum, $\tau(\lambda)$ is the spectral dependence of the transmission coefficient in the optics, $\varepsilon(\lambda)$ is the spectral characteristic of the quantum yield of the tube and λ is the wavelength in μm.

It is known that the light sensitivity of a camera can be improved by incorporating a light filter, the transmission coeffieient of which $\tau_\phi(\lambda)$ can have a value within the limits $0 \leq \tau_\phi(\lambda) \leq 1$, into its optical system. Let us find the characteristic $\tau_\phi(\lambda)$ of the optimum light filter.

Taking the spectral characteristics of the light filter into account, formula (3.43), for the signal-noise ratio, takes the form

$$q = A \frac{\int_0^\infty G_1(\lambda)\tau_\Phi(\lambda)d\lambda}{\left[\int_0^\infty G_2(\lambda)\tau_\Phi(\lambda)d\lambda\right]^{\frac{1}{2}}}, \qquad (3.44)$$

where /156

$$A = l_f \; d\sqrt{\frac{\pi T}{4h_0 C_0 \Delta l_2^2}}, \quad G_1(\lambda) = E(\lambda)\tau(\lambda)\varepsilon(\lambda)\lambda, \quad G_2(\lambda) = B_\Phi(\lambda)\tau(\lambda)\varepsilon(\lambda)\lambda.$$

We transform formula (3.44) to the form

$$q = A\frac{Q_{1\,max}}{Q_{2\,max}^{\frac{1}{2}}}\,\frac{\int\limits_0^\infty g_1(\lambda)\,\tau_\phi(\lambda)\,d\lambda}{\left[\int\limits_0^\infty g_2(\lambda)\,\tau_\phi(\lambda)\,d\lambda\right]^{\frac{1}{2}}}, \qquad (3.45)$$

where $g_1(\lambda) = \frac{Q_1(\lambda)}{Q_{1\,max}}, \quad g_2(\lambda) = \frac{Q_2(\lambda)}{Q_{2\,max}}.$

It follows from expression (3.45) that the task of maximization of the signal-noise ratio is reduced to finding the maximum of the functional:

$$y\{\tau_\phi(\lambda)\} = \frac{\int\limits_0^\infty g_1(\lambda)\,\tau_\phi(\lambda)\,d\lambda}{\left[\int\limits_0^\infty g_2(\lambda)\,\tau_\phi(\lambda)\,d\lambda\right]^{\frac{1}{2}}}. \qquad (3.46)$$

In other words, that characteristic $\tau_\phi(\lambda)$ of the light filter must be found, at which quantity (3.46) will have a maximum. This characteristic will be the desired spectral characteristic of the optimum light filter.

The light filter transmission function sought $\tau_\phi(\lambda)$ changes within the limits $0 \leq \tau_\phi \leq 1$.

We present the transmission function in the form

$$\tau_\phi(\lambda) = P\{z(\lambda)\}, \qquad (3.47)$$

where $z(\lambda)$ is a certain function of light wavelength; $P\{z(\lambda)\}$ is the operator by means of which function $z(\lambda)$ is converted into function $\tau_\phi(\lambda)$.

We place the following conditions on operator $P\{z\}$:

(a) $P\{z\}$ is a monotonic, continuous, differentiatable function, determined along the entire numerical axis:

(b) $P\{-\infty\} = 0$, $P\{\infty\} = 1$.

It flows from these conditions that

$$\left.\frac{dP\{z\}}{dz}\right|_{z=-\infty} = \left.\frac{dP\{z\}}{dz}\right|_{z=\infty} = 0.$$

We will seek the maximum of functional (3.46) by the variation method. Substituting (3.47) in (3.46) and representing function

$z(\lambda)$ in the form $z(\lambda) = z_0(\lambda) + \alpha\eta(\lambda)$, we obtain an expression /157
for functional (3.46):

$$y\{z_0(\lambda),\ \alpha\} = \frac{\int\limits_0^\infty g_1(\lambda) P(z_0(\lambda) + \alpha\eta(\lambda))\, d\lambda}{\left[\int\limits_0^\infty g_2(\lambda) P(z_0(\lambda) + \alpha\eta(\lambda))\, d\lambda\right]^{\frac{1}{2}}}, \tag{3.48}$$

where z_0 is a function yielding the maximum functional (3.48); $\eta(\lambda)$ is an arbitrary bounded function; and α is the variational variable.

It is evident that, at $\alpha = 0$, expression (3.48) will have a maximum. Therefore,

$$\left.\frac{dy\{z_0(\lambda),\ \alpha\}}{d\alpha}\right|_{\alpha=0} = \frac{2\int\limits_0^\infty g_1(\lambda)\eta P'\, d\lambda \int\limits_0^\infty g_2(\lambda) P\, d\lambda - \int\limits_0^\infty g_2(\lambda)\eta(\lambda) P'\, d\lambda \int\limits_0^\infty g_1(\lambda) P\, d\lambda}{2\left[\int\limits_0^\infty g_2(\lambda) P\, d\lambda\right]^{\frac{1}{2}}} = 0,$$

where $P = P\{z_0(\lambda)\};\ \ P' = \dfrac{dP\{z_0(\lambda)\}}{dz_0}$. (3.49)

It can be shown that expression (3. 49) reverts to zero with any function $\eta(\lambda)$, only in the event $P'\{z_0(\lambda)\} = 0$. In this case, function $z_0(\lambda)$ takes a value of either $+\infty$ or $-\infty$, in which the change in value takes place only by a jump. Correspondingly, function $\tau_\phi(\lambda)$, in accordance with expression (3.47), can take only the values 0 or 1, jumping from one value to the other.

Therefore, we will seek the transmission function of a optimum-light filter in the form of rectangles (Fig. 3.19). We write down the following system /158
of equations for finding N rectangular sections of transparency of the optimum filter:

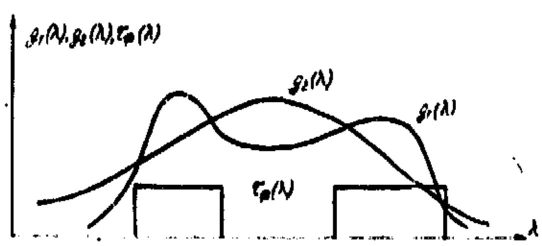


Fig. 3.19 Calculation of regions of transparency of optimum spectral light filter

$$\left|\begin{array}{l} 2g_1(\alpha_j)\sum\limits_{i=1}^{N}\int\limits_{\alpha_i}^{\beta_i} g_2(\lambda)\, d\lambda = g_2(\alpha_j)\sum\limits_{i=1}^{N}\int\limits_{\alpha_i}^{\beta_i} g_1(\lambda)\, d\lambda, \\ 2g_1(\beta_j)\sum\limits_{i=1}^{N}\int\limits_{\alpha_i}^{\beta_i} g_2(\lambda)\, d\lambda = g_2(\beta_j)\sum\limits_{i=1}^{N}\int\limits_{\alpha_i}^{\beta_i} g_1(\lambda)\, d\lambda, \end{array}\right. \tag{3.50}$$

where $j = 1, 2, \ldots, N$; α_1, β_1 are the boundaries of the i-th section of transparency of the light filter.

Separating the equations in system (3.50) from one another in pairs, we obtain

$$\frac{g_1(\alpha_1)}{g_2(\alpha_1)} = \frac{g_1(\beta_1)}{g_2(\beta_1)} = \frac{g_1(\alpha_2)}{g_2(\alpha_2)} = \frac{g_1(\beta_2)}{g_2(\beta_2)} = \ldots \frac{g_1(\alpha_N)}{g_2(\alpha_N)} = \frac{g_1(\beta_N)}{g_2(\beta_N)}.$$

It is evident from this that the limits of the sections of transparency of the optimum light filter are located at identical levels of the signal-background ratio (Fig. 3.20) $g_1(\lambda)/g_2(\lambda)$.

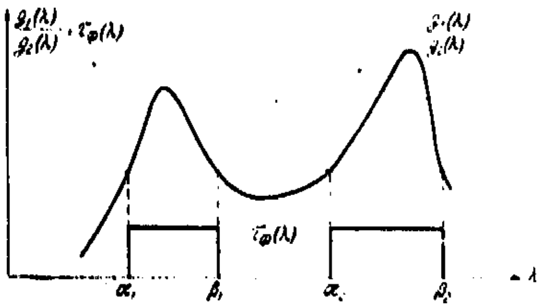


Fig. 3.20 Regions of transparency vs. spectral contrast $g_1(\lambda)/g_2(\lambda)$

In this manner, for calculation of the spectral characteristics of the optimum light filter, it is sufficient to solve system of equations (3.50).

The solution of system (3.50), in general form, can be carried out by computer.

We examine the estimate of light sensitivity of television cameras reproducing, not a point object, but an object of complex shape. In television, an estimate of light sensitivity usually is carried out from the experimentally determined light characteristics. In vidicon cameras, measurement of the light characteristics takes place on a background of video signal current shot noise and video preamplifier noise:

$I^2_{\eta\Sigma} = 2\,eI_sF_e + I^2_{\eta a}$, where $I^2_{\eta a}$ is the video amplifier noise power, corrected to its input and $I^2_{\eta\Sigma}$ is the total noise power at the video amplifier inlet.

Because of the presence of noise, measurement of the amplitude /159 of the video signal pulse I_s, formed by the camera tube, is carried out in the confidence interval $\pm\Delta I_p$, equal to (Fig. 3.21): $\Delta I_p = q_{thr}I_{\eta\Sigma}$, where q_{thr} is the threshold signal-noise ratio, with a given probability of detection of a video pulse.

Taking a finite confidence interval into consideration permits, first of all, determination of the working exposure range, from TB_{thr} to TB_{lim} of the light characteristic, as is illustrated in Fig. 3.21a. The numerical parameter of the light characteristic is its steepness, equal to the derivative continuous characteristic: $S(TB) = dI_s/d(TB)$, A/lux·sec.

The steepness of the light curve permits calculation of the video signal current from the decrease in illumination ΔB on background B_ϕ (Fig. 1.17), by the approximate formula

$$\Delta I_s = S(TB_\phi)T\Delta B \quad \text{at} \quad z = \text{const.} \tag{3.51}$$

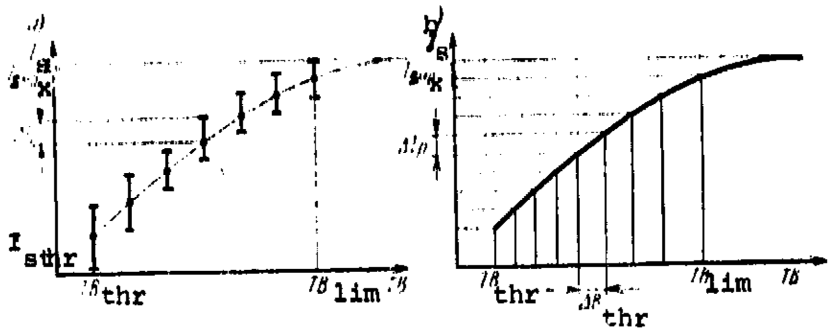


Fig. 3.21 Determination of working exposure range and threshold illumination decrease from light characteristics

The signal-noise ratio from a large, low-contrast detail, taking (3.51) into consideration,

$$q_\Delta = \frac{\Delta I_s}{I_{n\Sigma}} = \frac{S(TB_\phi)T\Delta B}{I_{n\Sigma}}. \tag{3.52}$$

Following sensitometry, which was developed in photography [35], we plot the light characteristic on a logarithmic scale. The steepness of this characteristic is the dimensionless quantity

$$\gamma = \frac{d \log I_s}{d \log BT}$$

or

$$\frac{\Delta I_s}{I_s} = \gamma \frac{\Delta BT}{BT} = \gamma k \quad \text{at} \quad k \ll 1. \tag{3.53}$$

Steepness γ is called the contrast coefficient,[1] since it characterizes the change in contrast by formula (3.53). /160

Frequently, the threshold contrast light sensitivity, estimated by the value of the threshold contrast of a large detail reproduced by the camera, is used. The threshold contrast value of a large detail is found by equating the signal-noise ratio (3.15) to the threshold value:

---

[1] In photography [35], steepness γ is called the characteristic curve gradient, and value of the gradient in a rectilinear section the contrast coefficient. This separation has not been adopted in television.

$$\frac{k\gamma}{2\nu_r}\sqrt{\frac{\rho}{bW_a}} = q_{thr}$$

or

$$k = \frac{q_{sa}}{\gamma q_{sa}} = \frac{q_{sa}\, 2\nu_r \sqrt{bW_a}}{\gamma \sqrt{\rho}}. \tag{3.54}$$

With increase in background illumination, the value of $\gamma(B_\phi)$ decreases and the value of $\rho(B_\phi)$ increases, which generates a minimum in threshold contrast (3.54). It has already been noted in section 3.3 that, in a slow-scan vidicon camera, a signal-noise ratio $Q_{sa} = 800$ has been achieved. At $Q_{thr} = 4$ and $\gamma = 1$, this should provide for achievement of a threshold contrast in a large detail equal to:

$$k = q_{thr}/\gamma q_{sa} = 0.005. \tag{3.55}$$

The threshold contrast in small details can be determined for a suboptimum camera, from the condition of resolution of two small details, by means of equation (2.89). In an estimate of light sensitivity of a suboptimum camera from the threshold contrast in small and large details, allowance for the light spectrum should be included, similar to the way it was done above for a quasi-matched camera.

It is evident that prospects of use of television light receivers are expanding considerably, under conditions of bringing to reality a calculated potential light sensitivity, exceeding the light sensitivity of the human eye, both for receiving radiation invisible to the eye and for obtaining a lower contrast threshold.

The latter is being achieved, by means of reducing the noise factors of the video amplifier W_a and tube W_{tt}, increasing the photoeffect quantum yield ϵ and increasing the efficiency of formation of the video signal current η_s.

3.5 Forced Erasure of Camera Tube Target

Forced erasure of charges, remaining on a camera tube target after a single readout, has been noted above, is opening the way to storage of larger charges, since it permits elimination of tube persistence. Reduction in time T_{er} of erasure and correction of the target increases efficiency of the slow-scan method of video signal spectrum compression (see formula (3.5)). /161

The memory characteristic (see Fig. 3.4) permits evaluation of erasure of the latent image stored on the target, by means of spreading of the charges over the target and a number of other factors, under conditions of absence of a readout beam. Inclusion of a readout

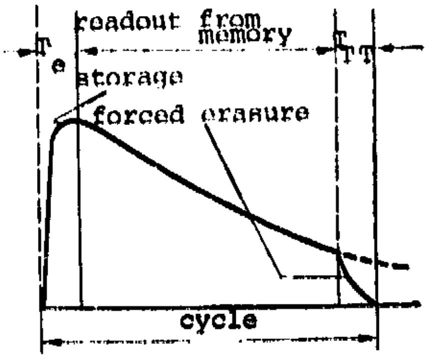


Fig. 3.22 Time characteristic of television storage device

beam and the readout process itself, of course, accelerates erasure of the latent image.

The time characteristic of television storage device (Fig. 3.22) the leading front of which is the storage device response characteristic and the rear, the readout response characteristic, is a major characteristic, determining the stage of a slow-scan operating cycle of the transmitting camera. The erasing effect of the readout beam is evaluated by the readout response characteristic, which shows the decrease in amplitude of the video signal in the first, second, etc., readout from memory of a stored image.

In supericonoscope and superorthicon type camera tubes, erasure of the stored latent image is facilitated by the fact that, in the process of erasure, storage of a new image takes place. The erasing effect of a new recording on the old one in these tubes is explained by redistribution over the target of secondary electrons, knocked out by photoelectrons.

The residual image, which appears in supericonoscopes and superorthicons with nonequilibrium recording, is the most serious interference to storage of a new image on the target in vidicon type camera tubes. This interference can be fought in two directions:

-- By elimination (even if partial) of the cause of formation of the residual image on the target: Decrease of readout persistence, by means of development of appropriate tube targets and increase in the erasing effect of the readout beam;

-- By incorporation of a special target erasure and correction operation in the camera tube operating cycle.

The first direction involves camera tube improvement, and it is determined by achievements in vacuum technology, and the second, camera tube circuit development.

It is simplest to carry out the target erasure and correction operation in the supericonoscope. For this, it is sufficient to irradiate the target with a uniform flux of fast photoelectrons (i.e., $\sigma > 1$), over a period of time equal to T_{tt}, at a zero potential difference between the collector and the signal plate. The erasure and correction time T_{tt} can be decreased in this case to the exposure time, i.e., $T_{tt}/T_e \sim 1$. /162

In the superorthicon, a tube with a two-sided target, the readout and correction operation consists of irradiation of both sides of the target with a stream of fast electrons [87].

The slowest rate of latent image erasure in the process of readout of a television storage device by an electron beam is characteristic of vidicon type camera tubes. The vidicon readout response is determined by the following factors. Large charges are accumulated on the photo layer in a vidicon during exposure, for erasure of which by the readout beam, repeated switching of the target is required; this is caused by the so-called switching component of the vidicon readout response. Moreover, the latent image formed by exposure within a semiconductor photo layer, by means of the internal photoeffect mechanism, does not disappear instantaneously after exposure, but at a finite rate; this is caused by the so-called photoelectric component of the vidicon readout response.

The existence of two components of the vidicon readoutresponse hampers the search for a method of forced erasure and correction, to provide for operation of a vidicon with a long memory in a slow-scan camera. For the purpose of simultaneous elimination of switching and photoelectric readout persistence, it has been proposed [88] to include a photo layer erasure and correction operation in the vidicon operating cycle, consisting of two successive stages: Illumination of the photo layer by uniform light from an illuminator and rapid switching of the photo layer by an electron beam with a current of maximum amplitude. In this case, the advisability is assumed of changing the accelerating voltage between the signal plate and the cathode, during rapid switching of the photo layer by the electron beam, as well as the possibility of installing a second, more powerful electron projector in the vidicon.

Development of the erasure and correction operation was a major stage in experimental research in the field of use of a long-memory vidicon in the slow-scan method of image transmission. It permitted designers of slow-scan cameras, using only one type of long-memory vidicon, to build slow-scan cameras with tube operating cycles of various lengths. By means of the erasure operation, it became possible to build a slow-scan television transmitting apparatus (single-tube or multitube), which has a time cycle changing 163
according to program, for the purpose of observation of objects with various rates of motion.

As an example, we present a structural diagram of a slow-scan camera (Fig. 3.23), with a vidicon type camera tube, the prospects for use of which in space television are especially high, by virtue of its small size and simplicity of insuring unattended operation. The presence of a controllable photoshutter, auxiliary vidicon photo layer illuminating lamps, camera mode program control unit and narrow-band video amplifier, having an optimum vidicon load

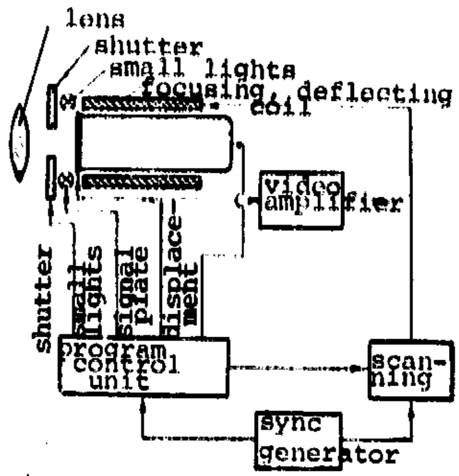


Fig. 3.23 Structural diagram of slow-scan vidicon camera

resistance and optimum transmission function, are specific for this camera. The program control unit forms pulses, which enter the photoshutter, photo layer illuminating lamps, signal plate and vidicon projector (to increase the beam current during correction) and scanning. In the correction process, scanning is preserved, and the scanning rate of the switching beam increases sharply, for example, by means of supplying a sinusoidal voltage, with a frequency a hundred times greater than the line frequency.

3.6 Storage and Readout in System with Controllable Field

The capacity of a camera tube target to store large charges can be increased, not only by means of developing a new type of target, for example, through use of thinner storage films in the tube, but by means of increasing the intensity of the potentials in the large and small details of the latent image. Intensity of the potentials of the latent image stored on a target dependson the field created around it by the stored charges and potentials on the tube electrodes. The field strength in the region of the target is determined by the potential differences (see Figs. 1.7 - 1.11):

-- For vidicons, on the plate U_{sp} and thermocathode U_c;

-- For superorthicons, on the collector grid (target grid) U_{tg} and thermocathode U_c;

-- For supericonoscopes, on the cylindrical collector /164
U_{cc} and the signal plate U_{sp}.

Depending on the type of camera tube, one of the three potentials U_{cc}, U_{tg} or U_{sp} can be selected as the field controlling potential U_c. To preserve the generality of the discussion, we will call this the control potential U_c. The program unit controlling operation of the slow-scan transmitting camera (see Fig. 3.23) shifts the control potential U_c during the cycletime, and it establishes the value of U_c separately for storage, readout from the memory and target erasure.

We consider the effect of the control potential in the camera tube on the storage process. The mechanism of accumulation of charges on the supericonoscope and superorthicon target is characterized by **great similarity** in the part using the secondary electron emission phenomenon ($\sigma > 1$). The difference in the supericonoscope and superorthicon storage sections is reduced to a difference in shape and location of the secondary electron collector: It is cylindrical around the supericonoscope target and in the form of a grid located next to the target in the superorthicon. If the target has an initial potential U_{10} before the storage process, by selection of the control potential U_c on the cylindrical collector in the supericonoscope or on the target grid in the superorthicon, an accelerating voltage $U_c - U_{10}$ can be created, for removal of secondary electrons from the target during storage. This storage mode with removing field, which significantly decreases redistribution of secondary electrons over the target, is called nonequilibrium registration [89]. Establishing nonequilibrium registration conditions in the supericonoscope and superorthicon permits:

-- Increasing the image potential intensity with a given exposure and a given contrast, by means of linearization of the storage device response characteristic and use of targets with a large secondary emission coefficient;

-- Increasing the maximum image potential intensity under conditions of corresponding increase in exposure.

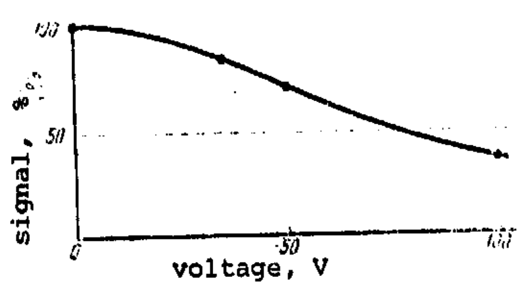


Fig. 3.24 Decrease in image potential intensity on supericonoscope target for storage of charges in a braking field

An increase in the control potential U_c is accompanied by gradual saturation of the secondary electron current from the target to the collector, which creates noncriticality in selection of control potential values (on a cylindrical collector and a target grid) during the storage (exposure) time. In a number of cases, there may be interest in buildup in a braking /165
field ($U_c - U_{10}$) < 0, in which secondary electrons are returned to the target. A graph, reflecting the decrease in image potential intensity ΔU on a supericonscope target, with decrease in control potential U_c on the cylindrical collector, from 0 to -100 V, is presented in Fig. 3.24 [70]. As is evident from the figure, in a strong braking field ($U_c \sim -100$ V), the decrease in image potential intensity is slight. This is evidence that interelement redistribution of secondary electrons on the target plays the principal role in the storage process in a strong braking field. The presence of interelement redistribution is confirmed by the form of the video signal from black-white jumps, which becomes differential.

The material presented on nonequilibrium registration in the supericonoscope and superorthicon refers to vidicon, although the storage process in these tubes does not use the secondary emission phenomenon, but the internal photoeffect. An increase in control potential on the vidicon signal plate ($U_c = U_{sp}$) relative to the cathode, from 10 to 100 V causes an increase in potential intensity in large and small details of the image being stored. With increase in control potential U_c to 100 V, the video signal is considerably distorted by interference from the dark currents in the target [30].

The value of the control potential U_c which the slow-scan camera program control unit sets during storage, is quite uncritical. The criticality of setting the control potential increase sharply in changing to the process of readout of the stored image. We consider the effect of the control potential U_c on the readout process. We return to formula (1.8) for this. The control potential U_c, together with the average component U_{av} of the potential image participates in creation of a constant field around the target and, thereby, affects the video signal amplitude[1]

$$I_s(t) \approx S(U_c - U_{av}) \Delta U I_n, \tag{3.56}$$

where I_n is the readout beam current.

It follows from formula (3.56) that, by regulating the control potential U_c (i.e., by regulating the steepness S), the video signal amplitude can be changed. In order to reveal the pattern of this effect, the following relation was obtained experimentally [70]

$$\frac{I_s}{I_{max}} = \varphi(U_c - U_{av}) \Big|_{\substack{\Delta U = \text{const},\\ I_n = \text{const}.}}$$

The experiment consisted of estimating the change in amplitude of a video signal formed in memory readout by a beam I_n, of a constant potential drop on the target ΔU, at different values of the control potential U_c. Measurement results applicable to readout by the hard /166 beam in the supericonoscope ($U_c = U_{cc}$) are presented in the form of the graph in Fig. 3.25. In these measurements, constancy of the potential drop ΔU and background potential U_ϕ was achieved by maintaining constant storage conditions on the target. The potential drop formed from the edge of an opaque black strip, with a width of 0.1 line length (i.e., $U_\phi = 0$), at constant exposure $BT_e = 2$ lux·sec.

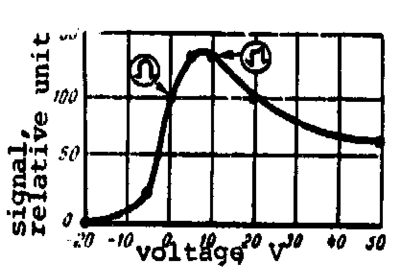


Fig. 3.25. Superconoscope readout efficiency.

The experimental curve in Fig. 3.25 demonstrates the existence of an optimum take-off field, i.e., existence of an optimum value of the control potential $U_{c\,opt}$, at which the amplitude of the video signal generated in the memory readout

[1]For simplicity, we assume $U_c = 0$ for a vidicon or suporthicon and that $U_{st} = 0$ for the supericonoscope.

process reaches a maximum. The memory readout, with a control voltage $U_c > U_{c\ opt}$ or $U_c < U_{c\ opt}$, is accompanied by a decrease in video signal amplitude, because of reduction in readout efficiency.

The conclusion as to the existence of an optimum field for the readout process holds true, not only with reference to readout by a hard beam, but to readout by a soft beam (secondary emission coefficient less than one).

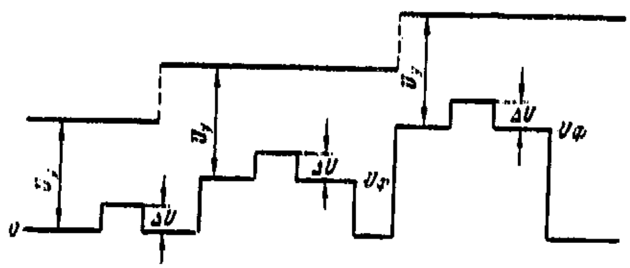


Fig. 3.26 Explanation of necessity of regulation of control potential in camera tube

Since, in the process of readout of a latent image, the readout beam encounters potential drops ΔU at different background potential levels U_ϕ, it is evident that the optimum value of the control potential $U_{c\ opt}$ must be regulated during the readout time, in accordance with the change in background potential U_ϕ (Fig. 3.26). Retention of a constant control potential value cannot provide maximum readout efficiency for low-contrast details at different background levels from black to white.

Setting the control potential U_c at the optimum, relative to the level of the background potential U_ϕ, on which an image detail being read out is located, with a potential drop ΔU, is a means of "subtracting" the background. This subtraction guarantees formation of the maximum video signal from low-contrast details on a bright background, i.e., it increases the contrast sensitivity of the television system. /167

3.7 Slow-Scan Camera Video Preamplifier

A television camera video preamplifier must guarantee the required amplification of the camera tube video signal, in the assigned video frequency band, with a minimum noise factor. Design of a video amplifier can be arbitrarily divided into three stages:

1. Selection of type of video amplifier input cascade and calculation of camera tube load resistance;

2. Selection of method of design and calculation of input circuit linear distortion correction cascades;

3. Calculation of video frequency band and video amplifier noise factor.

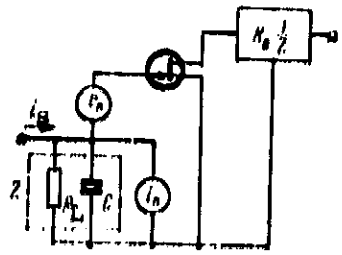


Fig. 3.27 Diagram of field-effect transistor input cascade of video amplifier

We obtain the calculation formula for the noise factor of a video amplifier with a p-n junction field-effect transistor input cascade. A diagram explaining derivation of the noise factor formula is represented in Fig. 3.27. The noise of the field-effect transistor is represented in the form of a series generator of noise voltage e_n and a parallel generator of noise current i_n [90].

For calculation of the video amplifier noise factor, the shape of its amplitude-frequency characteristic (AFC) must be known. We select a flat AFC to the upper frequency limit F_{lim}, beyond which the AFC decreases smoothly. Such a video amplifier will have the equivalent frequency band $F_e = bF_{lim}$ (see section 2.5).

We find from the diagram in Fig. 3.27 that the square of the noise current led into the output of a video amplifier with a flat AFC,

$$I_{na}^2 = \frac{4kT^o}{R_L} F_e + \int_0^{F_e} \left[i_n^2 + e_n^2 \frac{1 + (\omega R_L C)^2}{R_L^2} \right] df, \tag{3.57}$$

where $k = 1.38 \cdot 10^{-23}$ Joule/degree is the Boltzmann constant, T^o is the absolute temperature, i_n is the equivalent root mean noise current of the field-effect transistor with an open input circuit, e_n is the equivalent root mean noise voltage of the field-effect transistor with a short circuited input circuit, R_L is the tube load resistance, $\omega = 2\pi f$ is the cyclic frequency, C is the input capacitance of the amplifier, with the tube capacitance taken into account. /168

With high tube load resistances in the medium and high frequency region $(\omega R_L C)^2 \gg 1$, expression (3.57) is simplified:

$$I_{na}^2 = \frac{4kT^o}{R_L} F_e + \int_0^{F_e} [i_n^2 + e_n^2 (\omega C)^2]\, df. \tag{3.58}$$

We find the value of i_n^2 from the static cutoff current I_{co} of the field-effect transistor, by means of the Schottky formula:

$$i_n^2 = 2eI_{co} \tag{3.59}$$

where e is the charge of an electron.

Substituting (3.59) in (3.58) and dividing I_{na}^2 by the video signal current shot noise, we obtain an expression for the video amplifier noise factor

$$W_a = 1 + \frac{\frac{4kT^\circ}{R_L} F_e + 2e I_{co} F_e + \int_0^{F_e} e_n^2 (\omega C)^2 \, df}{2e I_s F_e}, \tag{3.60}$$

where I_s is the video signal amplitude, determined from the light characteristic of the vidicon.

It is clear from expression (3.60) that, with specific input cascade parameters, I_{co}, e_n and C, a reduction in the video amplifier noise factor can be achieved, by means of increasing the tube load resistance to values close to the internal resistance of the transmitting tube.[1] The transmitting tube internal resistance depends on the target capacitance, readout rate and size of the active section of the readout beam (see section 3.3). Therefore, in each specific case, the tube load resistance should be selected as a compromise between permissible values of it relative to the camera tube internal resistance and reduction in the thermal noise power of the resistance.

If the tube internal resistance is high, selection of the load resistance can be made from the conditions, in which the resistance thermal noise power is 2.5 times less than the video amplifier input cascade inherent noise. Further reduction in the resistance thermal noise power, negligibly decreasing the resulting video amplifier /169 noise factor, leads to an unjustified increase in load resistance and to complications of correction of the input circuit frequency distortions. Setting the terms in the right side of expression (3.58) in a 1:2.5 ratio, with allowance for (3.59), we obtain a formula for calculation of the load resistance

$$R_L = \frac{10kT^\circ F_e}{2e I_{co} F_e + \int_0^{F_e} e_n^2 (\omega C)^2 \, df}. \tag{3.61}$$

We substitute formula (3.61) in (3.60) and, after certain transformations, we obtain a formula for calculation of the noise factor

$$W_a = 1 + 1.4 \frac{2e I_{co} + \frac{1}{F_e} \int_0^{F_e} e_n^2 (\omega C)^2 \, df}{2e \left(\frac{I_s}{F_e}\right) F_e}. \tag{3.62}$$

The results of calculation of the noise factors by formula (3.62), for typical values of the parameters $C = 25$ pF, $I_{co} = 4 \cdot 10^{-11}$ A and e_n (curve 2, Fig. 3.28) are presented in Fig. 3.12.

Analysis of relation (3.62) shows that there is an optimum value of the video amplifier equivalent frequency band $F_{e\ opt}$, at which its

---

[1] If the tube capacitance C_{tt} is greater than the input capacitance of the amplifier C_a, reduction in the video amplifier noise factor can be achieved by parallel connection $n = C_{tt}/C_a$ of identical input cascades.

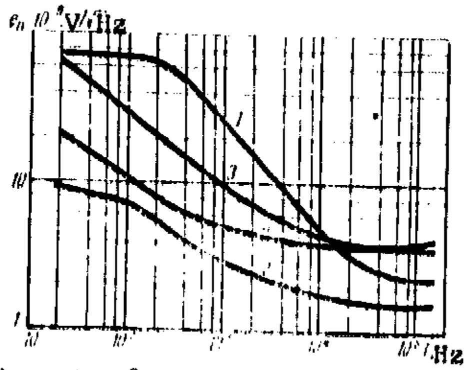


Fig. 3.28. Typical curve of equivalent noise voltage e_n of field-effect transistors with two types of p-n junction (1,2), 6N28B-V tubes (3) and a 6S51N-V nuvistor (4) vs. frequency with short-circuited input.

noise factor W_a is at a minimum. In the first approximation, not taking function $e_n(f)$ into account, and equating the first derivative of noise factor $W_a(F_e)$ to zero, we obtain

$$F_{e\,opt} = \frac{1}{C e_n}\sqrt{\frac{3eI_{co}}{2\pi}}. \qquad (3.63)$$

It is evident from expression (3.63) that the optimum value of the video amplifier equivalent frequency band depends only on the input cascade parameters.

An increase in noise factor (Fig. 3.12) with narrowing of the frequency band $F_e < F_{e\,opt}$, is connected with the dominant rôle of the shot noise of the cutoff current I_{co} and, with broadening of the frequency band $F_e > F_{e\,opt}$, with the field-effect transistor channel thermal noise e_n. The value of $F_{e\,opt}$ (see formula (3.63)) can be increased only by means of a decrease in the video amplifier input capacitance and the field-effect transistor noise. /170

We compare the conditions of achieving the minimum noise factor in a slow-scan video amplifier, with different types of input cascades.

A reduction in the camera tube signal current in the slow-scan mode leads to a situation, in which the input cascade leakage current can prove to be comparable to the signal current. In this case, the leakage current shot noises will prevail over other noise sources in the input cascade, limiting the decrease in video amplifier noise factor. To eliminate this limitation, it is sufficient to have the video amplifier input cascade leakage current a factor of 1-2 less than the camera tube signal current. With a slow-scan vidicon signal current on the order of 10^{-9} A, this requirement is satisfied only by electronic tubes and field-effect transistors.

Typical results of measurement of the grid current of electronic tubes and the cutoff current of a modern field-effect transistor with p-n junctions are given in Figs. 3.29 and 3.30.[1] Analysis of the measurement results shows that the cutoff current of the field-effect transistor at moderate "dischage-discharge" voltages ($U_{dd} \leq 10$ V) and electronic tube grid currents at high negative voltages on the grid $|U_g| > 2$ V, are between 10^{-10} and 10^{-11} A, over a wide range of change in input signal. /171

[1] MOP transistors are not consiuered, because of the poor noise parameters e_n and i_n, compared with those of field-effect transistors having a p-n junction [91].

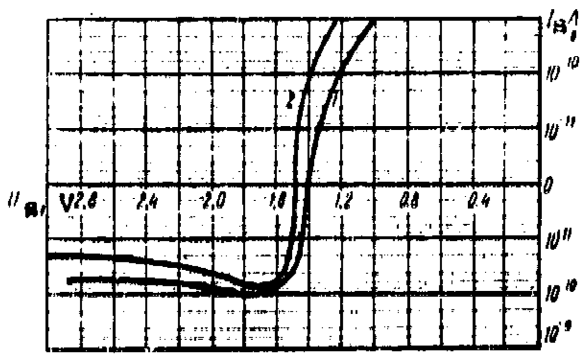


Fig. 3.29 Typical curve of grid current I_g vs. grid viltage U_g of 6N28B-V tubes (1) and 6S51N-V nuvistor (2) at U_a = 40 V, U_1 = 6.3 V

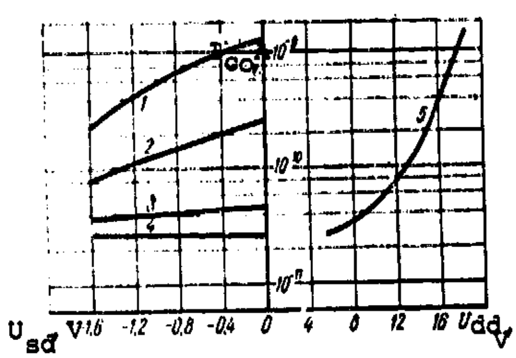


Fig. 3.30 Typical curve of shutoff current I_{sh} of a modern silicon field-effect transistor with p-n junction vs. "shutoff discharge" U_{sd} and U_{dd} "discharge-discharge" voltages: 1. U_{dd} = 18 V; 2. U_{dd} = 15 V; 3. U_{dd} = 10 V; 4. U_{dd} = 5 V; 5. U_{sd} = 0

Another parameter determining the noise factor of a video amplifier is the equivalent noise voltage e_n of the input cascade. In narrowing the frequency band in slow-scan systems, a significant limitation on decrease in video amplifier noise factor is introduced by that region of the noise power spectral density, which is caused by the flicker effect in an electronic tube or by excess noise of the 1/f type in semiconductor devices.

Typical results of measurement of the equivalent noise voltage e_n of electronic tubes and field-effect transistors of two types, with a short circuited input, are shown in Fig. 3.28. The equivalent noise voltage of the electronic tubes was measured under conditions of small grid currents.

The equivalent noise resistance frequently is used as a calculation parameter, characterizing the noise properties of a device. This has been justified for a wide frequency band, where the flicker effect and excess noise can be disregarded. In a narrowed frequency band, their effect must be taken into account.

Calculation of the equivalent noise resistance

$$R_n = \frac{\int_0^{F_e} e_n^2\,df}{4kT^\circ F_e}$$

shows that, with decrease in equivalent frequency band from 10^5 to 10^3 Hz, the resistance R_n of a field-effect transistor (curve 2, Fig. 3.28) increases from 180 to 1600 ohm, and R_n of the nuvistor (curve 4), from 1000 to 4000 ohm. A sharp change in the equivalent noise resistance creates indeterminacy in calculation of the noise factor of narrow-band, slow-scan video amplifiers from the value of R_n. Use of the equivalent noise voltage e_n in calculation formula (3.60), with account taken of its dependence on frequency, permits the value of an actual video amplifier noise factor in a given frequency band to be obtained.

It is evident from Figs. 3.29 and 3.30 that, at comparable values of the grid and cutoff currents ($4 \cdot 10^{-11}$ A), the equivalent noise voltage in modern field-effect transistors is approximately half that of electronic tubes. Consequently, to achieve a minimum noise factor, use of field-effect transistors in the output cascade of a slow-scan system video amplifier is preferable. /172

Narrowing the equivalent frequency band of a video amplifier is accompanied by monotonic increase in the tube load resistance (see formula (3.61)). The value of the tube load resistance at $F_c \leq 10^5$ Hz reaches several hundred megohms, which requires an effective correction of linear distortions of the input circuit.

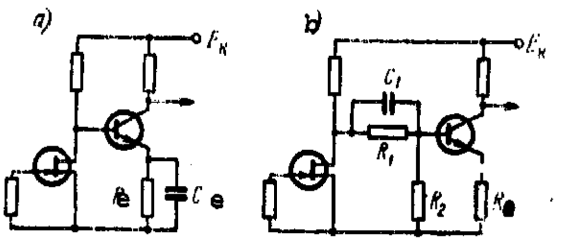


Fig. 3.31 Diagram of correcting cascades

Two methods of building correcting cascades are known: With frequency-dependent negative feedback in the emitter circuit (Fig. 3.31a) and with a frequency-dependent divider in the base circuit (Fig. 3.31b). The criterion for selection of the construction method can be the frequency band, in which the cascade accomplishes the correction, and the magnitude of its noise factor. For the region of the operating frequency of a slow-scan system, analysis of the diagrams in Fig. 3.31 is easily reduced to expressions, suitable for practical use.

The frequency and phase characteristics of the input circuit of the video amplifier have the respective forms:

$$K(f) = \frac{1}{\sqrt{1 + (\omega\tau_{in})^2}}, \quad \varphi(f) = \mathrm{actan}\, \omega\tau_{in}. \tag{3.64}$$

where $\tau_{in} = R_L C$ is the input circuit time constant.

We find the frequency and phase characteristics of the correcting cascades in Fig. 3.31, for the case when the internal resistance of the input signal source is considerably less than the input resistance of the correcting cascade, and the correcting cascade load serves as a high resistance, shunted by small capacitance. In practice, it is easy to satisfy these conditions by connection of an emitter repeater at the input and output of the correcting cascade. Then, for the diagram in Fig. 3.31a, the frequency and phase characteristics, respectively, are:

$$K(f) = \frac{\frac{r_e}{R_e}+1}{\sqrt{\left[\frac{r_e}{R_e}+\frac{1}{1+(\omega\tau_e)^2}\right]^2+\frac{(\omega\tau_e)^2}{[1+(\omega\tau_e)^2]^2}}},$$

(3.65)/173

$$\varphi(f) = \arctan\frac{\frac{\omega\tau_e}{1+(\omega\tau_e)^2}}{\frac{r_e}{R_e}+\frac{1}{1+(\omega\tau_e)^2}},$$

where $\tau_e = R_e C_e$ and r_e is the differential resistance of the emitter junction.

For the diagram in Fig. 3.31b:

$$K(f) = \frac{\frac{R_2}{R_1}+1}{\sqrt{\left[\frac{R_2}{R_1}+\frac{1}{1+(\omega\tau_1)^2}\right]^2+\frac{(\omega\tau_1)^2}{[1+(\omega\tau_1)^2]^2}}},$$

$$\varphi(f) = \arctan\frac{\frac{\omega\tau_1}{1+(\omega\tau_1)^2}}{\frac{R_2}{R_1}+\frac{1}{1+(\omega\tau_1)^2}}, \quad (3.66)$$

where $\tau_1 = R_1 C_1$.

By satisfying the inequalities:

$$\frac{1}{1+(\omega\tau_e)^2} \gg \frac{r_e}{R_e}, \quad \frac{1}{1+(\omega\tau_1)^2} \gg \frac{R_2}{R_1} \quad (3.67)$$

and

$$\frac{r}{R} \ll 1, \frac{R_2}{R_1} \ll 1 \quad (3.68)$$

the frequency and phase characteristics of the correcting cascade in Figs. 3.31a and 3.31b take the respective forms

$$\tilde{K}(f) = \sqrt{1+(\omega\tau)^2}, \quad \tilde{\varphi}(f) = \arctan\omega\tau, \quad (3.69)$$

where $\tau = \tau_1 = \tau_e$.

Making $\tau = \tau_{in}$, we obtain the correction of the frequency and phase distortions of the input circuit.

Inequality (3.68) is easily satisfied in practical circuits, but inequality (3.67), only in a restricted frequency band. We find the frequency band, in which the cascades accomplish the correction, from the conditions, when the drop in frequency characteristics (3.65) and (3.66) at the upper limit (compare with (3.69)) equals 3 dB, i.e.,

$$\frac{K(f)}{K(0)} = \frac{1}{\sqrt{2}}. \qquad (3.70)$$

Substituting expression (3.69) and, in turn, (3.65) and (3.66) in (3.70), after certain transformations, allowing for condition (3.68), we obtain the respective expressions

$$f_{lim} = \frac{1}{2\pi C_e r_e}, \qquad (3.71)$$

$$f_{lim} = \frac{1}{2\pi C_1 R_2}. \qquad (3.72)$$

At frequency f_{lim}, the input resistances of the correcting cascades, allowing for satisfaction of condition (3.68), are, respectively: /174

$$R_{in} = r_b + \beta r_b \approx \beta r_e, \qquad (3.73)$$

$$R_{in} = R_2, \qquad (3.74)$$

where r_b is the transistor base resistance and β is the current gain.

Under condition $C_e = C_1$ and equality of the output resistances of formulas (3.73) and (3.74) at f_{lim}, the frequency band (3.71) of the cascade with frequency-dependent negative feedback in the emitter circuit is β times wider than frequency band (3.72) of a cascade with a frequency-dependent divider in the base circuit. If $C_1 < C_e$, the gain decreases. Taking the simplicity of the electrical circuit into account as well, use of the cascade in Fig. 3.31a for correction of linear distortions of the input circuit is more advisable.

If one correcting cascade is insufficient to obtain the assigned video frequency band, several such cascades can be included. The time constant τ_{ek} of the feedback circuit of each succeeding cascade is found from the value of the limiting frequency of the preceding cascade:

$$\tau_{ek} = \frac{1}{2\pi f_{lim\,k-1}},$$

where k = 1, 2, . . ., m.

In using the correcting cascade of Fig. 3.31a, the assigned video amplifier frequency band can be obtained by the sequential connection of a correcting cascade of resistance R'_e, with non-shunting capacitance, in the emitter circuit. The limiting frequency of such a cascade is decreased to a value of

$$f_{\text{lim}} = \frac{1}{2\pi C_e r'_e}, \tag{3.75}$$

where $r'_e = r_e + R$.

The total phase and frequency characteristics of a corrected video amplifier, with allowance for the frequency and phase characteristics of the input circuit (formula 3.64) and the correcting cascade (formula 3.65), upon satisfaction of condition (3.68), will take the form:

$$K(f) = \frac{1}{\sqrt{1+(\omega\tau_e)^2}},$$

$$\varphi(f) = \arctan\frac{\omega\tau_e}{\frac{r_e}{r'_e}(\omega\tau_e)^2+1} - \arctan\omega\tau_e$$

The steepness of the drop of the AFC of such a video amplifier beyond the limiting frequency f_{lim} is proportional to the first power of the frequency, and its phase characteristic is nonlinear.

There are several methods of forming a video amplifier linear phase characteristic. One of the simplest is connection of a Γ-form low-frequency filter at the video amplifier output (Fig. 3.32). In the no-load mode, the frequency characteristic of the filter /175

$$K_\Phi(f) = \frac{f_0/f}{\sqrt{\left(\frac{f_0}{f} - \frac{f}{f_0}\right)^2 + \frac{1}{Q^2}}}, \tag{3.76}$$

where $f_0 = \frac{1}{2\pi\sqrt{L_\Phi C_\Phi}}$ is the resonance frequency of the circuit,

$$Q = \frac{\sqrt{L_\Phi/C_\Phi}}{R + R_\Phi}$$

is the Q factor of the circuit (R_g is the output resistance of the preceding cascade).

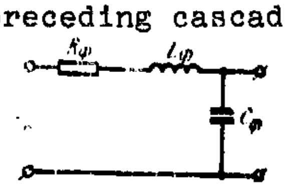


Fig. 3.32 Γ-form low-frequency filter

The phase characteristic of the filter

$$\varphi_\Phi(f) = \arctan\frac{1}{Q\left(\frac{f_0}{f} - \frac{f}{f_0}\right)} \tag{3.77}$$

is close to linear with a circuit Q factor $Q = 1/\sqrt{2}$.

If the frequency band of the corrected video amplifier $f_{lim} \gg f_0$, its frequency and phase characteristics will be determined by the frequency and phase characteristics of the Γ-form filter at its output. Substituting the value $Q = 1/\sqrt{2}$ in (3.76), we find the total AFC of the video amplifier

$$K(f) = \frac{1}{\sqrt{1 + \left(\frac{f}{f_0}\right)^4}} \qquad (3.78)$$

The steepness of the decrease in AFC of such a video amplifier beyond the limiting frequency f_0 is proportional to the second power of the frequency, and its phase characteristic (3.77) is linear. Integrating [92] expression (3.78), we find the value of the equivalent video amplifier frequency band relative to the 0.707 level; $F_e = 1.86 f_0$.

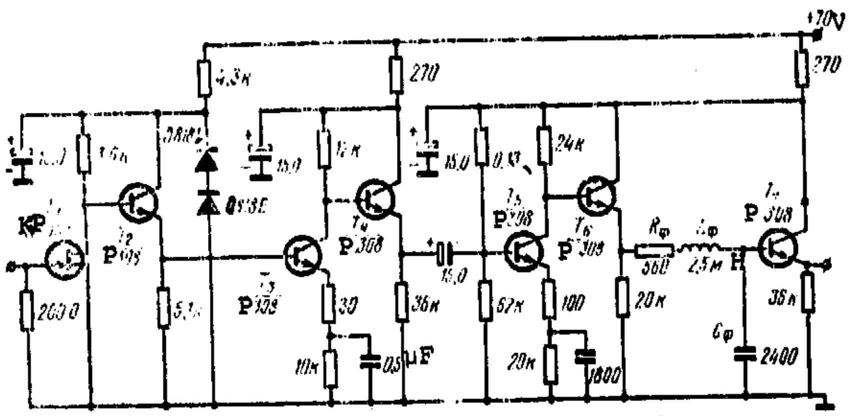


Fig. 3.33 Diagram of video preamplifier of slow-scan vidicon system

An example of the design of a video preamplifier for a slow-scan vidicon camera, with equivalent video frequency band $F_e = 0.12$MHz, is presented in Fig. 3.33. The first cascade T_1, a type KP303 field-effect transistor, has a gain of 10. The vidicon load resistance, calculated by formula (3.61), included in transistor T_1 cutoff circuit, equals 200 Mohm. Correction of the linear distortions of the input circuit is accomplished by cascades T_3 and T_5. The frequency band (3.71) corrected by cascade T_3 is 4.4 kHz and, by cascade T_5, 0.7 MHz. The gains of cascades T_3 and T_5 are identical and equal to 1.2. The limiting frequency of the Γ-form filter at the output of the video /176 amplifier $f_0 = 65$ kHz. The noise current to the video amplifier input is $6.8 \cdot 10^{-12}$ A, and the video amplifier noise factor, at a vidicon signal current, $I_s = 2 \cdot 10^{-9}$ A, equals 1.6.

3.8 Video Signal Processing in Intermediate Video Amplifier

The limitation of the peak power of the onboard radio transmitter makes the problem of effective use of its dynamic range urgent. This problem is solved, by means of special video signal processing systems in an intermediate video amplifier, following a video preamplifier with aperture correction. Video signal $U_{c1}(t)$, of arbitrary shape, with a duration of several lines T_{line}, entering the intermediate video amplifier input, is presented in Fig. 3.34a. Video signal $U_{c1}(t)$ has a white envelope $U_w(t)$ and a black envelope $U_b(t)$. We determine discrete values of the envelopes at moments of time $k\Delta t$ in the following manner: $U_w(k\Delta t) = \max\{U_{c1}(t)\}$ at $t \in [(k-1)\Delta t, k\Delta t]$, $U_{b}(k\Delta t) = \min\{U_{c1}(t)\}$, $k = 1, 2, \ldots$, where Δt is the regulated interval.

The largest and smallest values of the video signal $U_{c1}(t)$ are reckoned on the basis of return signals in regulation interval Δt, which can be equal to the duration of several lines, one line or a part of it. Interpolating the discrete values, we obtain continuous envelopes $U_w(t)$ and $U_b(t)$, which characterize the degree of efficiency of use of the dynamic amplitude range. Having obtained the values of the video signal envelopes, it can now be processed, which is written mathematically, in the form of the expression [93, 94] /177

$$U_{c2}(t) = [U_{c1}(t) - U_b(t)] \frac{U_{c\,max}}{U_w(t) - U_b(t)}, \qquad (3.79)$$

where $U_{c1}(t)$ and $U_{c2}(t)$ are the video signal voltages at the input and output of the intermediate video amplifier, $U_{c\,max}$ is the greatest value (amplitude) of the video signal in the transmission time.

The first processing operation, accomplished by formula (3.79), is calculation of the equivalent limitation and subsequent fixing of the video symbol with respect to envelope $U_b(t)$ (Fig. 3.34b). The limited video signal in Fig. 3.34b does not contain a black envelope. The second processing operation by (3.79) is division of the limited video signal (3.34c) by the difference of the two envelopes. /178 As a result of the division, the video signal takes the form shown in Fig. 3.34c. The video signal in Fig. 3.34c has a distorted shape, with respect to the input video signal in Fig. 3.34a. However, these distortions, which frequently are permissible, provide for more effective use of the dynamic range. Moreover, discrete values of the $U_w(t)$ and $U_b(t)$ envelopes can be transmitted by an auxiliary narrow-band radio channel or even simply, by means of modulation of the synchronization pulses at the receiving point. Then, signal processing can be accomplished at the receiving point, which is the reverse of that which was done by formula (3.79), and these distortions can be eliminated.

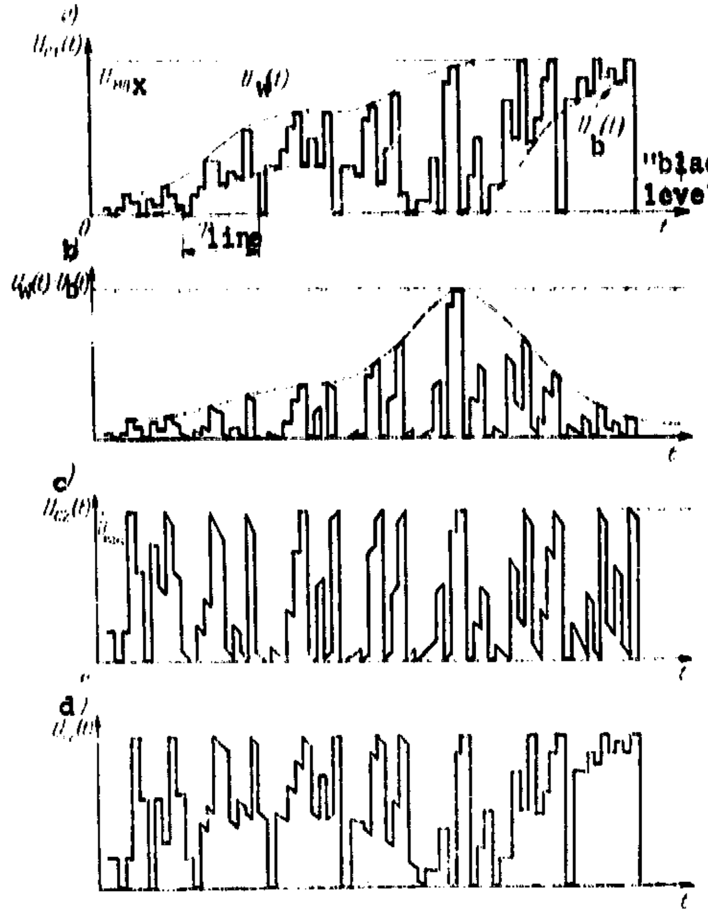


Fig. 3.34 Processing video signal in intermediate video amplifier

The signal processing, done according to formula (3.79), is put into practice with a video loop automatic parameter regulation circuit (APR), combining automatic video signal cutoff level regulation (ACR) and automatic regulation of its gain (AGR). Automatic cutoff level regulation in essence extracts from the video signal precisely that part of it, which is included between the envelopes. Measurement of the value of the black envelope is provided for in it, which is considered the current parameter of the video signal, and control of it, by means of level cutoff, which is the video amplifier parameter. Automatic gain regulation (AGR), as is well-known, stabilizes the amplitudes of signals entering its input. A device for determination of the difference in the envelopes $U_w(t) - U_b(t)$ and control of it by means of the video amplifier gain is provided in it. The envelope difference determines the change in gain over time, according to the formula

$$K_a(t) = \frac{U_{c\,max}}{U_w(t) - U_b(t)}. \qquad (3.80)$$

In this manner, these signal envelopes are controlling quantities in the automatic parameter regulation circuit, which act on the corresponding parameters of the video loop.

The presence of a video signal excess permits construction of an automatic regulation circuit, with prediction (extrapolation) of the video signal parameters. For example, in broadcast television, with high interframe excess, these video signal parameters of a transmitted frame permit the video signal parameters of the succeeding frame to be predicted with a high degree of accuracy. In slow-scan television systems, for which the absence of interframe excess is characteristic, prediction of the parameters in the regulation interval Δt, equal to the frame time, is impossible. Therefore, devices with by-the-line prediction of parameters are used in slow-scan systems; a high interline excess, inherent in all television systems with rectangular raster and image discretization in the frame direction, is used in them. In such devices, the video channel parameters, in transmission of the video signal of the k-th/179 line, are matched to the parameters of the preceding signal of the (k-1) line, with account taken of probable prediction errors. Automatic parameter regulation of this class is statistical, in the nature of the connections between the signal parameters and channel parameters.

The class of automatic parameter regulation devices, in which the connection between the channel and signal parameters are determinate, for example, those assembled according to a scheme with preliminary image scanning, are among the deterministic devices. These devices are used in intraline automatic parameter regulation devices, characterized by small regulation intervals $\Delta t < T_{line}$, permitting use of existing line delays of a video signal before its transmission.

Measurement of the two envelopes and processing of the signal by formula (3.79) leads to complication of the onboard apparatus. Sometimes, for purposes of simplification of the apparatus, it is useful to limit oneself to extraction of only the white envelope $U_w(t)$ and accomplishing incomplete processing by the formula

$$U_{c3}(t) = U_{c1}(t) \cdot \frac{U_{c\,max}}{U_w(t)} . \qquad (3.81)$$

Putting signal processing by formula (3.81) into practice is simpler, and it is accomplished, by means of automatic regulation of only one intermediate video amplifier parameter, its gain. The video signal formed at the output is shown in Fig. 3.34d.

A high correlative connection between the low-frequency signal envelopes and the low-frequency component of the video signal spectrum corresponding to it in frequency is characteristic of certain types of images. This circumstance permits creation of simplified automatic gain regulation systems, which are controlled directly by the low-frequency components of the spectrum of the video signal itself.

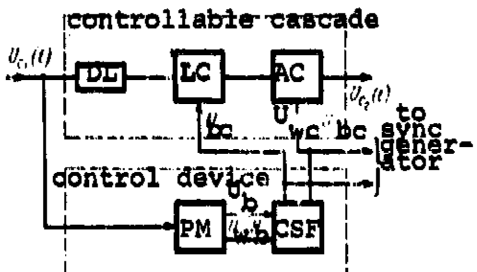


Fig. 3.35 Structural diagram of intermediate video amplifier automatic parameter regulation system

Compression of the dynamic range of the video signal through suppression of its low-frequency envelopes, is accomplished by means of automatic parameter regulation, a structural diagram of which is shown in Fig. 3.35. The system includes controllable video loop cascades and a control device. The controllable cascades contain a series-connected limit control (LC) and amplifier control (AC).

The limit control, acted on by the black level control signal (U_{lc}) changes the video signal cutoff level, extracting the most informative part. The amplifier control, acted on by control signal $U_{wc} - U_{lc}$, changes its gain in such a manner that, constant amplitude of the extracted portion of the radio signal is maintained at its output. The control device includes video signal parameter meters (PM) and a control signal forming device (CSF). The parameter meters measure the values U_b and $U_w - U_b$ in each regulation interval Δt, and these data are used in the control signal formation device, for formation of signals U_{lc} and $U_{wc} - U_{lc}$, which act directly on the video amplifier controllable cascades. In case of need, interpolation of the selection and restoration of continuous envelopes is carried out here. /180

A delay line (DL) is included in the intraline automatic regulation devices ($\Delta t < T_{line}$). By means of it, the video signal is delayed by the time necessary for formation of control signals.

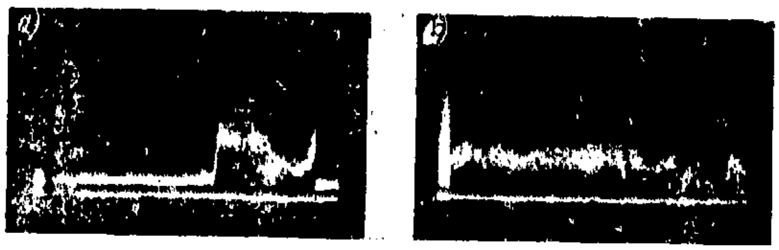


Fig. 3.36 Oscillograms of unprocessed video signal (a) and after processing (b)

The effect of the statistical, line-by-line automatic parameter regulation device is illustrated in Fig. 3.36. A video signal from the image is passed through the processing device, a part of which is closed by a neutral filter, of which the unprocessed image is evidence (Fig. 3.36a). It follows from the oscillogram that, in on-board processing, the amplitudes of the signals of all lines, including those eclipsed by the filter, are amplified to a value $U_{c\ max}$. As a result, both parts of the video signal have identical amplitudes (Fig. 3.36b). After this processing, the video signal has greater interference protection, with respect to communications line noises and observer noises.

4. TELEVISION SYSTEMS FOR SPACE RESEARCH /181

4.1. Phototelevision System

A phototelevision system was first used for obtaining television photos of the surface of the moon on 4 October 1959, by means of the nonreturnable interplanetary spacecraft (IS) Luna-3 [95]. Subsequently, phototelevision systems were used in the Soviet spacecraft Zond-3 and Luna-12 and in the American spacecraft Lunar orbiter [96].

Phototelevision photography of the surface of the moon was carried out during IS flyaround of the moon and from IS revolving in a selenocentric orbit. The purpose of these investigations consisted of study of the surface of the invisible side of the moon and obtaining photos of the moon with a resolution unavailable to astronomical observers from the earth.

A phototelevision system contains a camera, automatic photographic film developer, film-winding mechanism, image transmission apparatus and devices common to all television systems for synchronization, power supply, control and monitoring. A system for protection of photographic film from the effect of cosmic radiation also is a necessary element of a phototelevision system. With a relatively short storage time for the undeveloped photographic film, protection of it is provided by the spacecraft hull and by use of heavy metal cassettes. In those cases when, because of a high radiation dose, extremely high weight expenditures are required for protection of photographic film, a device providing for sensitization (activation) of the photographic film directly before exposure can be incorporated in the phototelevision camera.

Let us examine in greater detail the functioning of an onboard phototelevision apparatus, using the example of the phototelevision system of the interplanetary spacecraft Luna-3. The system includes an onboard phototelevision apparatus, radio channel and ground television receiver-recording station. A structural diagram of the onboard phototelevision apparatus is presented in Fig. 4.1. In the initial position, the photographic film is in cassette 1, protected from the effect of cosmic radiation by a layer of lead. /182 The film leader, passing through the film-winding loop, is fastened to takeup spool 13. After orientation of the interplanetary spacecraft on the moon, by command of the orientation device, the photography process begins. A curtain type shutter provides practically simultaneous exposure of the subject on the film, in the form of two frames, by means of two lenses with 200 and 500 mm focal lengths. Winding of the photographic film is accomplished by autonomous camera drive 2, in two-frame cycles. Simultaneously with exchange of neighboring pairs of frames, the shutter release time is changed, which provides for exposure with four different time values. The exposed photographic film is concentrated in interoperation storage device 3, calculated for its full length.

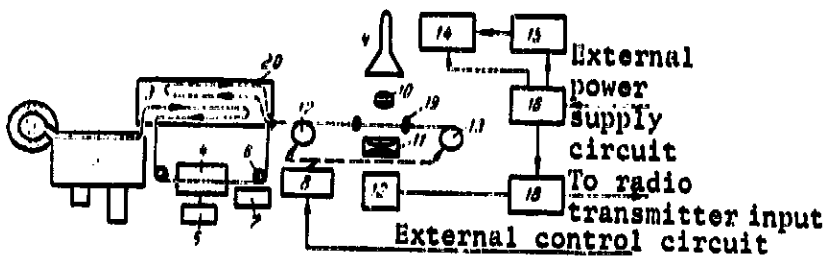


Fig. 4.1. Structural diagram of onboard phototelevision camera.

Upon completion of the photography, film developer 4 is automatically turned on. Its construction is as simple as possible, since development of the film is accomplished by a single-stage process. Active film-winding roller 17 and takeup spool 13 synchronized with it, draws the film through a reservoir filled with developer. Cavities filled with outside gas can form inside the developer, as reagent carried off by the film is consumed. Under weightless conditions, this can lead to disruption of the development process. Therefore, reagent consumption compensator 5 restores the initial amount of reagent and creates an excess pressure of 0.1 atm inside the developer. To keep the reagent from escaping from the reservoir, elastic seals, designed for this excess pressure, are provided at the film inlet and outlet.

The processed film enters a dryer, which consists of drum 6, with stabilized temperature and blowoff system with moisture absorbent 7. The completely developed, dry film is wound up on takeup spool 13. Upon completion of development of all of the photographic film exposed, the developing system is automatically switched off. Control of the developing process is accomplished /183
by mechanical program device 8. The drive of this device provides for drawing the photographic film through.

Upon command to transmit information, the photographic film begins a smooth movement in the opposite direction, passing through transmission window 19, in which it is leveled in the focal plane of the lens. The image is transmitted by means of a "traveling beam" device, consisting of miniature picture tube 9, reproduction lens 10 and condenser 11, collecting the light flux, modulated by the photographic negative, onto the photocathode of photomultiplier (PM) 12. To eliminate the effect of irregularities in sensitivity of the PM photocathode, the condensing optics projects a scanning element on any scanning base, in the form of a fixed spot, defocused over the entire PM area. Picture tube 9 has electronic line scanning (transverse to the photographic film). Longitudinal (frame) scanning is provided for by a precision mechanical film winding device. Electrical image signals from the PM output enter video amplifier 18, which filters the PM shot noise from the video signal, amplifies and forms it. The formed television signal is sent to the output of the onboard radio transmitter.

After passage through the transmission window, the photographic film again enters (loop 20) interoperation film storage device 3. Upon completion of transmission of all frames taken, the programming device automatically reverses the winding, and transfer of the photographic film is repeated. Uniformity in film winding is provided by a high-precision film winding mechanism and takeup spool compensator, which regulates the rate, depending on the thickness of the photographic film layer wound onto the drum.

Functioning of the television apparatus is provided by scanning 14, synchronization 15 and power supply 16 units. The onboard phototelevision apparatus is under telemetric control, giving information on the functioning of all links.

A general view of the onboard phototelevision apparatus used in the Luna-3 IS is shown in Fig. 4.2.

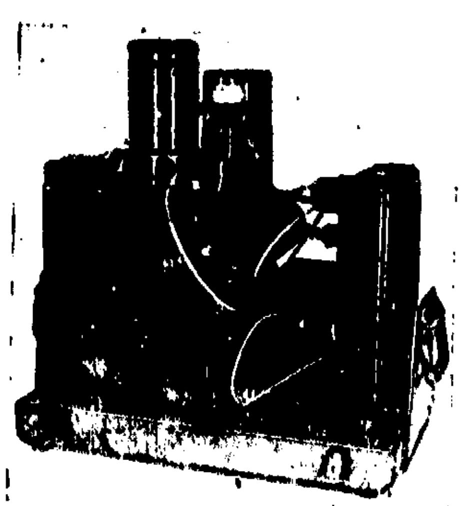


Fig. 4.2. Outward appearance of onboard phototelevision camera.

The quality of the /184 television photos, sizes, weight and reliability of the onboard phototelevision apparatus are determined to a great extent by the automatic photographic film developing and readout apparatus. The sensitometric characteristics of the photographic film used in phototelevision systems are selected, based on optimum coupling of the photographic film and readout device characteristics, from the point of view of guaranteeing the maximum signal-noise ratio and transmission of low-contrast jumps. Therefore, in distinction from standard photographic technology requirements, a maximum photographic film density of 1-1.2 and a contrast coefficient of 0.8-1, at a fog level of 0.1-0.3, can be considered to be acceptable.

Selection of the photochemical film developing process is determined by the requirements as to qualitative characteristics of the system, necessary for prolonged storage of developed film. The highest qualitative characteristics are provided by the usual multisolution process, in which the film is developed, washed (the developing reagents are removed), fixed and dried, in sequence. Exchange of reagents, temperature criticality of the process, and a large volume of reagents complicates design of an onboard developer: they increase its weight, size and energy consumption. If prolonged storage of the photographic film is not necessary, simplification of its development is possible, by means of elimination of washing and drying. A single-solution process, in which the photographic film is simultaneously developed and fixed, simplifies its developing technology. Considerably lower temperature criticality and independence of photo quality on development time permits a miniature, economical and highly reliable film developer to be created. However, photograph quality is somewhat reduced in this case; resolution is 35-40 lines/mm and the fog level, 0.2-0.3.

A diffusion process, similar to the process used in instant photograph cameras, is the most promising for space phototelevision systems. In this process, the developers are applied to the photographic film in a thin layer on the substrate. Diffusion takes place between the emulsion layer and reagent film, the rate of which depends on the intensity of illumination of the emulsion layer during development. In the diffusion process, the photographic film is developed and fixed and, then, after separation from the substrate, it enters the transmission camera.

Selection of one photographic film developing method or another is determined by the assigned qualitative characteristics of the overall phototelevision system, as well as by the weight and power resources of the onboard apparatus.

Video information can be read out from the photographic film, by means of a television transmitting camera of any type; however, in practice, a traveling beam device is used, as a rule. Such a device can be fabricated in an electronic version, using translucent tubes and, in the optico-mechanical version, where /185
scanning is accomplished by mechanical displacement of a point light source or its projection. The electronic system permits scanning over a broad range of rates, and it provides for simplicity in smooth or discrete change in its rate. Irregularities

in illumination of the picture tube screen and interference, caused by the discrete structure of the luminophores, reduce image quality, despite measures taken to correct these distortions. The optico-mechanical scanning version provides good signal uniformity, and it decreases the geometric and nonlinear distortions. However, limited scanning rates and the complexity in changing them narrows the field of use of this version.

Electronic line scanning, with mechanical frame scanning was used in the Luna-3 spacecraft apparatus. This permitted, together with the slow operating mode with narrow-band data transmission from great distances, incorporation of an accelerated, wide-beam mode of examining all fr mes of the film. In the Zond-3 IS television system, operating at low rates, optico-mechanical line and frame scanning were used.

The problem of control of the photographic film condition, the quality of its processing and preflight testing of the television channel is highly critical, since these processes cannot be controlled by normal telemetric methods. This problem is solved by preliminary preparation of the photographic film before it is loaded into the apparatus. On the section of photographic film located in the initial position of the apparatus in the transmission window, a lined globe is applied, permitting determination of the resolution of the channel during preflight preparation, without turning on the film-winding mechanism. Television test pattern 0249 was exposed beforehand, on a section of unexposed film, located outside the protective cassette. Comparison of the fog levels (the white signal) in the image with the fog level of sections stored in the cassette permits estimation of the effect of radiation on the film. A frame number corresponding to the frame, a sensitometric wedge and reference lines for taking account of geometric distortions are applied to each section of the photographic film. An impressed disk of the visible side of the moon, corresponding in diameter to a size, which would be obtained by photography from an altitude of 50,000 km, with a short-focus lens installed in the apparatus, is placed after the 40th frame. The test pattern is again exposed on the following frame. These frames must also be developed aboard the spacecraft. A test pattern developed under ground conditions then follows and, on the section set in the transmission window after completion of the developing process, a lined globe, also developed earlier.

Application of the elements enumerated onto the photographic film permits information to be obtained in sequence on all processes taking place in the onboard camera. By turning the camera on at the end of photography and film developing, a signal of the lined globe is transmitted, by which the channel is tested and the ground recording apparatus is prepared. After turning on the film /186 winding, the operation of the film-winding mechanism is checked, by the image of the test pattern developed on earth. The test pattern image developed under onboard conditions then following gives a complete idea of the quality of the developing process. The development parameters, taking account of the specifics of the lunar surface, are precisely defined from the image of the visible side of the moon, also developed under onboard conditions. Moreover, a comparison of the diameter of the disk printed on the film with the diameter of the disk of the back side of the moon permits precise determination of the altitude of the photography, with account taken of the actual geometric distortions of all links in the system: $H = 5 \cdot 10^4 \, D/D_\phi$, where H is the actual photography altitude, D is the diameter corresponding to an altitude of $5 \cdot 10^4$ m, and D_ϕ is the altitude obtained by photography.

The presence of the sensitometric wedges and reference lines in each frame permits allowance for possible changes in characteristics of the development process and geometric distortions, arising during operation. Elements located at the start of the film, as has already been pointed out, permit allowance for the effect of radiation, testing the degree of stability of the television channel during the period of transmission of the entire film, as well as accomplishment of preflight test, without turning on the film winder.

The unique nature of video information from space requires reliable and high-quality recording of it on earth, as well as operating control of reception quality. Operating control is accomplished on video monitors, using a skiatron type tube. Recording is repeatedly duplicated, both by number of devices and by the difference in methods of it. Recording is carried out on a photorecording device, open device recording on thermochemical paper, on a videotape recorder, as well as by photographing the skiatron screen. The availability of different methods of recording guarantees comprehensive processing of the information.

There is interest in methods of ground processing of the results obtained. Photographs of better quality are obtained by direct photography of the picture tube screen onto motion picture film. However, videotape recording gives no less valuable results. The availability of a video signal recorded on magnetic film permits the masking effect of noise to be decreased to a considerable extent, by means of secondary processing of it, and it permits analysis of the image by signal cross sections at different levels. This assists in developing a number of formations on the surface of the moon, which are poorly distinguishable in the initial photos.

The following experiment was carried out, to test the authenticity of the decoding of television photos. The visible side of the moon was exposed on photographic film, under the illumination conditions of the photography of the back side of it. The photographic film was developed in a duplicate of the onboard /187 developer. The information from the photographic film was transmitted through an analog of the communications channel in which noise, recorded in a real communications session with the IS, interfered. Then, recording was accomplished by the same means as in actual reception. The decoders, not knowing beforehand the structure of the moon, were asked to decode the images and compile a map of the visible side of the moon from them. The results of the decoding demonstrated complete coincidence of the compiled maps with the actual situation. The circumstance that elements of the surface of the moon observed from earth on the edges of the lunar disk were on the photos is of great importance, for confirmation of the authenticity of maps of the back side of the moon and topographical tying in of the images obtained. An optical projection of an image of the visible side of the moon on a white globe and photography of this globe, at an angle corresponding to the angle of photography of the back side of the moon by the Luna-3 spacecraft, gave complete coincidence of the results for this zone, and it permitted precisely defining the topographical tie-in of the newly obtained formations on the back side of the moon.

Fig. 4.3. Television photos taken from Luna-3 spacecraft, with lens focal lengths of a) 200 mm, b) 500 mm.

It should be noted that photography of the back side of the moon on 4 October 1959 was carried out under unfavorable conditions, at half-moon, when, by virtue of the orthogonality of incidence of the sun's rays, there were no shadows, and the photography was carried out under the natural contrast of the lunar surface, which is extremely low. Despite this, photos were obtained (Fig. 4.3), providing a quite detailed interpretation of the structure of the back side of the moon. Repeated television photography of the back side of the moon was accomplished during the flight of the Zond-3 IS, with fundamentally the same phototelevision system, into which a number of schematic, design and technological changes were incorporated, based on accumulated experience. The photography conditions of the Zond-3 spacecraft were better, because of the shorter photography distance and "lateral" illumination of the surface of the moon by sunlight. This permitted television photos of higher quality to be obtained (Fig. 4.4). /188

Fig. 4.4. Television photo obtained from Zond-3 IS.

By means of the Luna-12 and Lunar orbiter phototelevision systems, television mapping of the surface of the moon was carried out, from spacecraft, revolving in a selenocentric orbit. The light sensitivity of the phototelevision system and the definition of the television photos of the surface of the moon proved to be completely adequate for successful scientific interpretation of them and for obtaining information necessary for landing of automatic machines and man on the surface of the moon.

The primary virtue of a phototelevision system, ensuring its successful use, is the production of television photos of high definition (over 10^6 elements/frame), with onboard apparatus of small dimensions, weight and energy consumption. The use of the phototelevision system for photography of the surface of a planet involves improvement of the onboard photographic equipment, in the direction of improving the protection from penetrating radiation. Improvement in the readout section of the onboard apparatus should proceed in the direction of reduction of losses of information, caused by the electronic traveling beam device or optico-mechanical scanner. For this purpose, for photographic film of large sizes, in which high definition is inherent, section-by-section transmission of the image is used, the idea of which was stated in work [97, p. 347]. Improvement in the traveling beam device permits loss of photographic resolution in a section of the image to be reduced to a minimum [98, 99].

Work is being carried out at the present time, in the field of electronic analogs of photographic film, not requiring complicated development processes (electronic tube with a strip target, electrographic layers, tape photoelectronic converters) [96]. /189 It should be noted that perfection of film development methods, information on them as to the temperature, electromagnetic or light effects and activation of photographic film before exposure can expand the prospects of use of photographic film in creation of television systems with intermediate image recording.

4.2. Narrow-Band Mechanical System

A narrow-band mechanical television system was first used for space research on the Luna-9 lunar spacecraft (LS) [100]. It was intended for obtaining close-up television photos of the surface of the moon, by means of the LS after soft landing of it on the lunar soil.

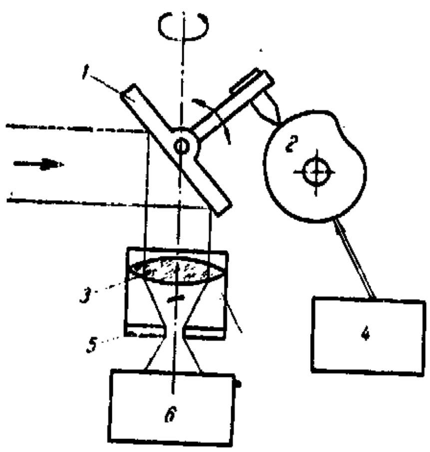


Fig. 4.5. Structural diagram of Luna-9 LS onboard television camera.

An optical-mechanical television system accumulates light energy during the period of transmission of a single element and, therefore, it has acceptable light sensitivity, only in transmission of slowly moving objects. A virtue of such a system is the maximum simplicity in construction, high uniformity of the image background, low-level of nonlinear and geometric distortions, linearity of the light characteristic, permitting photometric measurements to be provided in any portion of the radiation spectrum, with appropriate selection of radiation receiver.

The onboard camera of the mechanical television system of Luna-9 is a relatively simple device (Fig. 4.5). Its principle of operation is based on storage, accomplished by means of an electrical filter, the video amplifier.

The instantaneous field of view of the camera is formed, by means of lens 3 and chopping diaphragm 5. Selection of the diameter of the diaphragm, located in front of photomultiplier 6, is determined by the requirement for attaining the optimum value of the resolution of a camera, operating under the light conditions of the lunar surface. The system resolution depends on /190
linear distortions and on the signal-noise ratio. To reduce the linear distortions, it is desirable to decrease the diaphragm diameter; however, in this case, the signal-noise ratio decreases, because of the decrease in the light flux collected (see formula (1.3)). The combined action of these two factors determines the presence of the optimum resolution of the system, at given illumination and contrast values. In the television camera on the Luna-9 LS, an angular resolution of approximately 0.06° (3.6') was obtained. Since sections of the lunar surface, beginning at a distance of 1.5 m (Fig. 4.6) entered the field of view of the camera, the television system permitted resolution of the smallest details of the lunar surface, with dimensions of 1.5-2 mm, i.e., 200,000 times better than by telescope.[1]

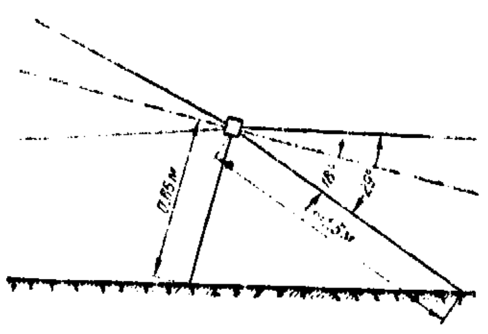


Fig. 4.6. Field of view of Luna-9 LS television camera.

Line scanning by rocking a mirror vertically within an angle of 29° was accomplished in the television system by means of cam 2, which provided for linear angular displacement of mirror 1 in a line scanning period of 1 sec, with a reverse travel of about 10%. In transmission of a panorama, the mirror was turned 360° around the vertical axis (frame scanning), in a time of 100 min. Mechanical line and frame scanning operates from motor 4, with stabilized speed of rotation. A panoramic television photo of the lunar surface is equivalent to a television frame containing 500 × × 6000 elements (Fig. 4.7).

The onboard camera of the Luna-9 LS television system /191
formed a narrow-band television signal, having a spectrum width of about 250 Hz, i.e., approximately equal to the video signal spectrum width in the Luna-3 IS phototelevision system.

---

[1] In ground photographic and visual observations by means of a telescope, details on the lunar surface of less than 300 m are not successfully resolved.

Fig. 4.7. Fragment of panoramic television photo obtained from Luna-9 LS.

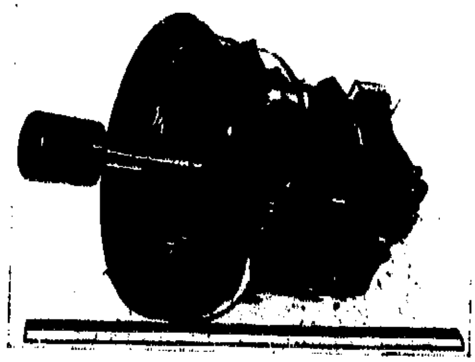


Fig. 4.8. General view of intermediate design LS onboard television camera.

A general view of one of the intermediate designs of a LS onboard television camera is shown in Fig. 4.8. Subsequent design finishing of the onboard camera permitted its weight, size and energy consumption to be reduced [101]. An outer view of the onboard camera used in the Luna-9 LS is shown in Fig. 4.9. The camera was fabricated, in the form of a small cylinder. Openings in the metal flange are used for attaching the camera to the LS hull. A narrow-band television signal from the camera was furnished to the onboard radio transmitter. Radio transmission was carried out at a frequency of 183.538 MHz, using frequency modulation. Reception, recording and processing of television signals was accomplished by a ground station, similar to the Luna-3 IS television system. A similar narrow-band optico-mechanical system also was used to obtain panoramic photos of the lunar landscape from the Luna-13 LS and photography of the surface of the moon from the Luna-19 spacecraft, which was in a selenocentric orbit. The small mass (1.3 kg) and low energy consumption (2.5 W) of the optico-mechanical camera of the television system permitted its use on Lunkhod-1, on which several such devices were installed.

The mutual locations of the television cameras installed on the Lunkhod-1 spacecraft are shown in Fig. 4.10, where the outlines of the upper cover of Lunkhod (top view) are given in dashes, and the cameras are designated in the following manner: Nos. 1 and 3 are vertical survey cameras, Nos. 2 and 4 are horizontal survey cameras and Nos. 5 and 6 are slow-scan /192

Fig. 4.9. Outer view of Luna-9 LS onboard television camera.

television system cameras [102]. Panoramic cameras Nos. 1-4 permit stereoscopic photos to be obtained with a 500-mm stereo base for cameras Nos. 1 and 2, several meters for cameras Nos. 1, 3 and 2 and 3 m for cameras Nos. 2 and 4. The images transmitted from panoramic cameras Nos. 1 and 3, having a panoramic angle of about 180°, are used for selection of the primary course of movement of Lunkhod, topographic terrain photography, investigation of structural peculiarities of the relief and the like. The vertical panoramic cameras (Nos. 2 and 4) are used for navigational purposes and observations of the front wheels of Lunkhod.

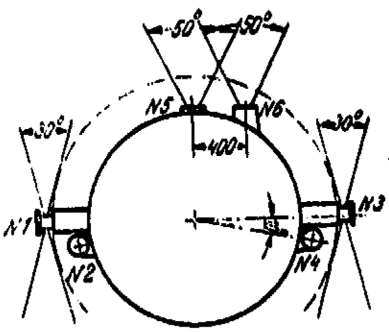


Fig. 4.10. Diagram of camera installation on Lunkhod-1 spacecraft (top view).

The principal qualitative characteristics of the panoramic cameras of the Lunkhod-1 spacecraft are significantly improved over those of the panoramic cameras of the Luna-9 and Luna-16 spacecraft. Thus, for example, because of decrease in the inlet aperture and chopper diaphragm diameter, the aperture characteristics of the camera were noticeably improved (Fig. 4.11) and, by means of substitution of the PM-54 by a PM-96, stability and sensitivity were increased. Moreover, automatic sensitivity control (ASC) is used in these cameras, by a signal with a time constant of 5-10 sec, and not by light.

For transmission of images of the sun by the vertical survey cameras, an additional operating mode was provided for, with disconnection of the ASC and reduction of sensitivity, by means of setting the appropriate PM power supply voltages. The basic characteristics of the panoramic cameras of the Luna-9, Luna-16 and Lunkhod-1 spacecraft are presented in Table 4.1.

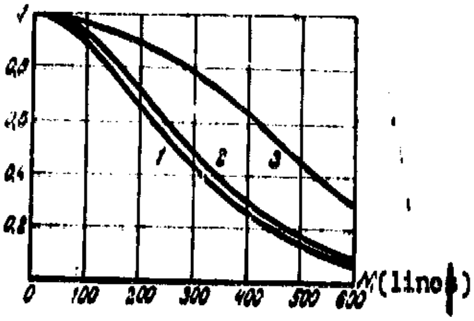


Fig. 4.11. Aperture characteristics of panoramic cameras: 1 - Luna-9; 2 - Luna-16; 3 - Lunkhod-1.

Scientific television equipment for meteorology and the national economy occupies an important place among space television systems. /193

TABLE 4.1.

Space-craft	No. of Cameras	Optical System Parameters: F mm	D/F	Focal Length, m	Field of View, degrees	Rated Definition, Element/Line	Modulation intensity at Rated Definition	No. of Lines in Complete Panorama	Transmission Rate, Lines/sec	Transmission Time of Complete Panorama, min
Luna-9	1	12.5	1:4	1,5—00	29(11+18)	500	0.3	6000	1	100
Luna-16	2	12.5	1:1.9	2,5	30(15+15)	300	0.3	6000	4;1	25;100
Lunkhod-1	4	12.5	1:6	1,5—00	30(15+15)	500	0.8	6000	4;1	25;100

General questions of design of similar systems are described in the next section. A description of only versions of equipment, constructed using optico-mechanical scanning are presented here, i.e., those which are narrow-band mechanical systems. One such system in the USSR is a meteorological television apparatus for direct transmission of cloud cover. A structural diagram of such equipment is presented in Fig. 4.12. By means of a scanning device

(SD), of the type used in the Luna-9 apparatus, and a photomultiplier, an image of a section of the surface of the earth is transformed into a video signal. To provide for transmission of a narrow-band video signal, displacement of the signal spectrum is accomplished in the amplifying and forming device (AF), by means of modulation or a specially generated subcarrier frequency voltage. Then, the signal, passing through radio transmitter RT, reaches the receiving apparatus (RA), to the output of which a phototelegraphic apparatus FTA is connected. A fragment of an earth cloud cover image obtained from this apparatus is presented in Fig. 4.13.

Fig. 4.12. Structural diagram of meteorological television apparatus for direct transmission of cloud cover image.

Fig. 4.13. Photograph of cloud cover of earth transmitted by television apparatus with optico-mechanical scanning.

Synchronization of operation of the onboard and ground apparatus is achieved, by means of high autonomous stabilization of the rotation rate of the rocker scanning mechanism and FTA drum.

For phasing FTA operation, a special pulse is used, which is mixed with the video signal and formed onboard, by means of a mechanical /194
contact, actuated from an eccentric disk, inserted into the same shaft as the cam, which swings the scanning mirror.

The basic parameters of the system are: line scanning frequency 0.5 Hz, field of view ±45°, resolution 1000 elements per line, or approximately 1.8 × 2.7 km on the surface of the earth at the subsatellite point, signal-noise ratio onboard at least 100, radio transmitter frequency 137.6 MHz, frequency deviation ±15 kHz. The system gives a normal image at sun heights beginning at 5°.

The camera used in the Nimbus-3 satellite is of interest. The shutterless, dissector camera, with a translucent photocathode and step scanning, is intended for continuously obtaining an image of cloud cover in the daytime, in the visible region of the spectrum (4800-6500 A). This camera is distinguished by high definition, accuracy of reproduction of half-tones and long service life.

The F-4012A dissector, with translucent photocathode, was developed by the ITT company. The dissector aperture is from 12.5 μm to 3.75 mm. With an aperture diameter of 25 μm, the actual resolution of the tube reaches 720 lines per centimeter. The use of a secondary electron multiplier permits tube sensitivity to be increased with a low noise level. The tube provides a modulation intensity of 25%, with a definition of 800 lines [106].

A virtue of the dissector camera is simplicity of construction: absence of a thermionic cathode, mechanical chopper (and other moving elements). The camera consumes half the power (12.5 W) of a vidicon camera. The focal length of the Tedea lens is 5.7 mm. The field of view is 108°. The dynamic range of the system is 100:1. Weight of the camera is 6 kg and of the optics, 1.2 kg. /195

The camera was designed, with allowance for providing operation of it in the APT system (scanning rate 4 Hz), and it is intended for obtaining images of sections of the surface of the earth, with an area of approximately 2,100,000 km^2 (840,000 square miles), with a resolution at the center of 3.2 km (2 miles), recording of these data aboard the satellite and transmission of them to earth during each pass of the satellite in the radio visibility zone of the receiving station, as well as for transmission of the images obtained on a real time scale (three times per day), to approximately 300 ground stations equipped with APT systems. The television apparatus of the first geostationary satellites, tested under the American ATS (Applications Technology Satellite) program, also are among the narrow-band mechanical systems.

The first experimental ATS-1 AES[2] was placed in a geosynchronous orbit on 7 December 1966. It had the following characteristics: line scanning was accomplished by means of AES orientation in space, by means of rotation of the satellite around an axis perpendicular to the orbital plane, at a rate of 100 rpm. Frame scanning was produced by means of slow turning of the telescopic system of the camera, with a frame time (2000 lines) of 20 min. Resolution at the subsatellite point is 3.6 km.

---

[2] [AES - artificial earth satellite.]

A PM was used as the converter [107].

A SSCC (spin scan cloud camera) color, optico-mechanical television camera, developed on the base of the ATS-1 AES television camera, was installed in the next AES of this series, ATS-3 (the launch of ATS-2 was a failure). In the color camera, the three color components were obtained, by means of use of three apertures. Fiber optics were used for transmission of red, blue and green color data to three separate photomultipliers. The corresponding light filters were installed on the PM. After transformation, the data on the three color components was transmitted to the receiving station over a single radio channel, by means of time compression.

The successful experience in operation of the television systems of the ATS-1 and ATS-3 meteorological satellites determined continuation of the work in building geostationary meteorological AES. At the present time, a new modification of a geostationary AES (Synchronous Meteorlogical Satellite), SMS, in which a two-channel scanning radiometer will be installed, to obtain images in the visible region of the spectrum (resolution about 3.5 km), has been developed and is being tested. It is proposed subsequently to increase the resolution in the /196 visible range to 0.8 km. The SMS orientation system basically preserves the characteristics of the ATS series AES. Besides obtaining images of the cloud cover, it is proposed to accomplish collection of data from automatic sensors, installed on dry land, ocean buoys, ships and other platforms, as well as to measure hard solar radiation and the terrestrial magnetic field, in the SMS AES.

4.3. Narrow-Band Electronic System

Narrow-band slow - s c a n systems, with an electron-beam transmitting tube of the vidicon type, have been used to obtain television photos of the surfaces of the moon and Mars and the cloud cover of the earth.

The task of television apparatus for meteorological purposes is to obtain operationally a picture of distribution and change in cloud cover on the surface of the earth, for compilation of long-range forecasts, forecasting moving storms, typhoons, etc., for which systematic information on the global scale in each synoptic period is necessary.

The interests of aviation, agriculture and other services of the national economy require knowledge of the state of the atmosphere and cloud cover at a given place and given time. Direct information is necessary for this. While only 1-2 receiving stations are sufficient for receiving information of the first type, for the second, a large number of receiving points, located in every locality where meteorological information is necessary. The requirement for information of global and local importance was generated initially in equipment of two types: a system of global collection of television information, with storage on videotape, and a direct transmission system.

Both types of television apparatus have been installed in AES with relatively low orbits, on the order of 600-1000 km. Increase in definition of television equipment and its installation in geostationary earth satellites is promising. The apparatus installed in such AES, having a circular orbit at an altitude of 35,800 km, in the plane of the equator, has a wide field of view, on the order of 130-140°, and it monitors a tremendous territory simultaneously. With the presence of several such AES, there can be global and direct information at any moment of time at one time. Moreover, because of the fixed location of the satellite above a single point on the earth, it is considerably easier to observe and register the dynamics of the cloud cover in the course of a day. A deficiency of such an observation system is the impossibility of round-the-clock observation.

Television systems with storage and with direct transmission of images are equipped with three types of sensors. The first is a vidicon type electronic tube television sensor with a memory. /197
Despite the differences in vidicons used, all sensors of this type are constructed similarly, an example of which is described below, in the Meteor system. The second type of apparatus is built around a dissector type electronic tube. The third type is apparatus with optico-mechanical scanning and transformation of the light signal, by means of a photomultiplier.

Each type of sensor has its virtues and deficiencies. Among the virtues of the optico-mechanical cameras are:

-- possibility of obtaining high definition, up to 3000-4000 lines;

-- possibility of operation without a wide-angle lens;

-- simplicity of providing a given scanning pattern, for correction of perspective distortions;

-- high light characteristic linearity;

-- possibility of wide variation in spectral characteristics, by means of replacement of PM by other radiation receivers;

-- practically complete absence of signal nonuniformity and spots on images;

-- possibility of use of stabilized AES rotation for line scanning;

-- simplicity of apparatus and high stability and reliability of operation connected with it.

Deficiencies of these systems:

-- use of mechanical scanning, leading to creation of a stray moment of rotation of the AES and to generation of mechanical flutter in the images;

-- possibility of superposition of images of neighboring lines on each other or omission of information between neighboring lines, because of time instability of AES position;

-- sharp reduction in sensitivity of the system with increase in resolution, because of decrease in light flux with linear decrease in aperture.

For optimum data transmission, a television system must be matched with the characteristics of the photography lens and transmission distance.

Cloud size and brightness are among the characteristics of cloud cover, which determine the choice of basic parameters of the television system. Cloud size determines the requirement for minimum detail size resolvable by the apparatus on the surface of the earth and their brightness, the dynamic light range of operation of the television camera. The satellite orbital parameters determine the requirements as to field of view of the camera and length of its operating cycle, which depends on the time interval of change in subject in the camera field of view.

As numerous observations, conducted for many years from earth and, then, from high-altitude aircraft and helicopters have shown, the cloud cover of the earth is very diverse in form and value of the reflection coefficients. An important task is determination of the minimum size of a cloud formation, /198 which is the optimum for transmission, by means of meteorological AES. From the data examined in Table 4.2, it can be assumed that this optimum size is 0.8 km. However, to obtain general surveys of cloud distribution, detect storm lines, movement of typhoons and other large formations, does not require such high detail. This is illustrated in Fig. 4.14. In the operational meteorological satellite system of the USA, for the purpose of increasing the area covered by each photo, the resolution of television cameras (AVCS) on the earth was selected as 3.2 km.

TABLE 4.2.

Cloud Form	Dimensions, km
Small cumulus clouds	0.07-0.08
Cumulus clouds in tradewind zone	0.8-2
Large cumulus clouds	0.8-3.2
Isolated cumulonimbus clouds	1.5-8
Mature storm clouds	9-16
Storm line	Up to 800 and over in extent

The illumination of cloud formations changes extensively, which is caused by direct illumination by sunlight, scattered atmospheric light and bias lighting by bright objects in the sky.

The primary portion of the illumination is determined by the sunlight and, therefore, it changes in accordance with the location of the sun (its angular position to the point being photographed). /199

The illumination will be the lowest during the polar night, and it amounts to about $1.5 \cdot 10^{-6}$ lux. In the full moon, illumination is 0.1-0.4 lux. With direct incidence of sunlight, illumination of cloud formations changes from approximately 10^5 lux, when the sun is in the zenith, to $5 \cdot 10^3$ lux, with a zenith distance of the sun of about 85°.

The contrast of cloud formations changes considerably, with respect to one another and to the surface of the earth. The coefficient of reflection (albedo) of clouds varies from 20 to 80%, depending on the rate of their vertical development. The coefficient of reflection of the surface of the earth changes from 2 to 70% for water basins, snow has about 90% and a forest, only 10%.

Parameters of the Meteor slow - s c a n television system satisfy the requirements as to apparatus for observation of the cloud cover on the daylight side (sunlight-illuminated) of earth. The long memory of the photoconductor target of the camera tube permits the system to operate in the slow - s c a n mode with shutter. Use of the shutter eliminates the necessity for complicated stabilization of the satellite. In an exposure time of 0.04 sec, the working range of exposure of the transmitting tube in the nonaligned mode is from 0.6 to 8 lux·sec.

Fig. 4.14. Photographs of cloud over of earth, transmitted from Kosmos-122 satellite: a) Cumuliform cloud cover of various structures (from fine-grained to dome-shaped); b) stratiform and cumuliform cloud cover; c) development of a cyclone in filling stage.

The contrast sensitivity and resolution of the camera tube provides for transmission of a high-quality image of the cloud cover, with a minimum size of details on the earth of 1.2 km. Slow memory readout over a period of 10 sec, of the image stored on the vidicon photo layer, permits the width of the video signal spectrum to be narrowed to 15 kHz. This narrow video frequency band provides for a minimum required transmitter power. The principal characteristics of the 1-inch vidicon camera system of Meteor are presented in Table 4.3.

To increase the field of view of the television system, while retaining the high angular resolution in it, two cameras operate simultaneously. Each camera is equipped with a type OKS-1-16 lens (focal length 16 mm and relative aperture 1:3), the optical axes of which are inclined at 19° to the normal. Owing to this, the field of view of the television system is 76°. Each camera contains a mechanical shutter, which is structurally joined to the lens, and has an electronic release. /200

TABLE 4.3. [96, 115]

Parameter Name	Parameter Value
Frame size on photo layer	11 × 11 mm
Resolution	At least 50 line/mm
Signal-noise ratio at 3 lux exposure	46 dB
Working exposure range	0.6–8 lux
Frame readout time	10 sec
Vidicon preparation time	50 sec
Length of camera operating cycle	60 sec
Video frequency band	15 kHz
Exposure time	From 0.025 to 0.04 sec
Photo layer spectral characteristic width	5000–6400 A

The operating cycle of each camera, equal to 60 sec is made up of the brief photo layer exposure during the return frame scanning course, memory readout for a period of 10 sec and erasure of the residual image on the photo layer during the remaining 50 sec. The forced erasure operation is not carried out, since the electron beam successfully prepares the vidicon photo layer in a time of 50 sec. The operating cycles of the two cameras are shifted relative to each other by 10 sec, i.e., exposure of the second vidicon begins after completion of readout of the first.

To extend the working exposure range of the television cameras, the lens diaphragms are regulated by command of the onboard sun height sensor. The lens diaphragms and delay can, besides, be changed by command from earth.

The outer appearance of the onboard television cameras of the Meteor system is shown in Fig. 4.15. Four cameras are joined in a single structure, two of which are reserves.

The Meteor system carries out a global survey of the state of the cloud cover over the entire surface of the earth. With a limited number of receiving points, this leads to the necessity for brief onboard storage of the information collected, for subsequent transmission in the zone of the receiving point.

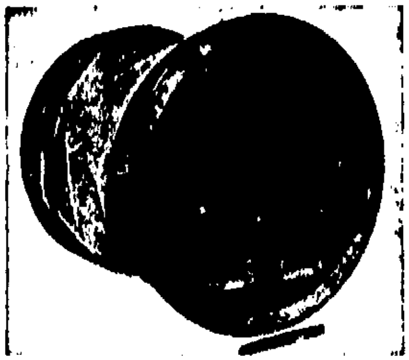


Fig. 4.15. Outer appearance of four onboard slow-scan cameras installed in Kosmos-122 satellite.

Therefore, the television apparatus of the Meteor system, a structural diagram of which is shown in Fig. 4.16, is a quite complicated set of scientific apparatus. Besides the transmitting cameras, the television camera includes a forming and control unit, data storage and reproduction unit and transmitter unit with antennas.

The shaping unit (Fig. 4.17) accomplishes preparation of the video signal for subsequent transmission to the ground receiving point, if the satellite is in the radio visibility zone, or to the memory in the storage unit. /201 The video signal, ampified by the camera preamplifier, enters a linear amplifier, in which tying in of its black level and vidicon dark current cutoff are carried out. Information on the vidicon dark current level is /202 transmitted with the video signal of the last frame in preparation of the photolayer and it is stored in the linear amplifier. Further, various service pulses (synchronizing, damping and correcting) and a code package on the number of each pair of frames are mixed into the video signal. The video signals from the two video preamplifiers of the operating pair of cameras are switched to the linear amplifier input, by means of which they continuously enter the shaping unit output.

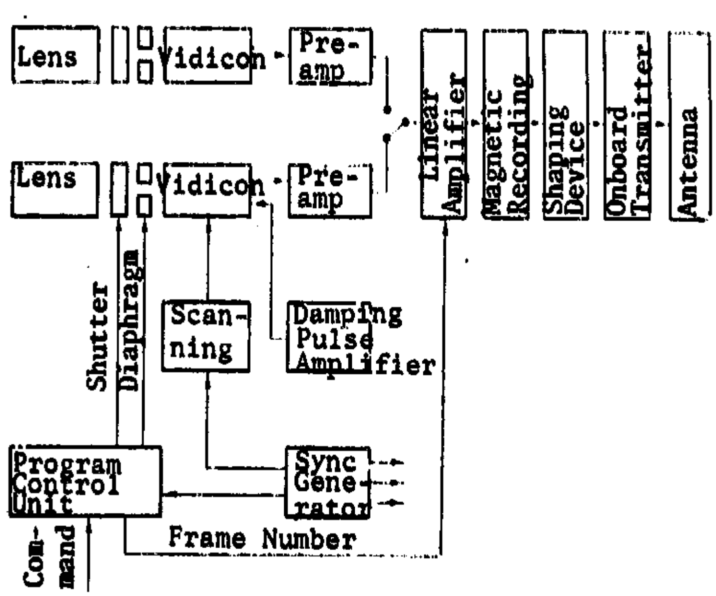


Fig. 4.16. Structural diagram of television apparatus of slow-scan system (units serving the second vidicon are not shown).

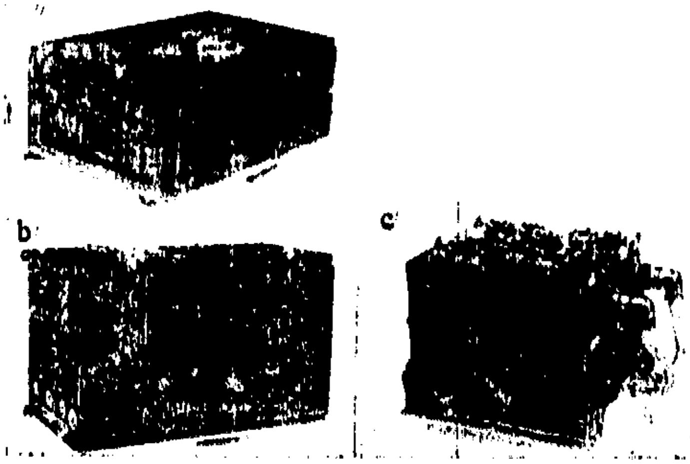


Fig. 4.17. Television apparatus of Kosmos-122, Kosmos-144 and Meteor satellites: a) Shaping and control unit; b) storage unit (magnetic recording); c) radio transmitter unit.

The control unit (Fig. 4.17) carries out automatic operation of the apparatus from the onboard program device, in which a portion of the permanent commands and a part of the variable ones, changeable by command from earth, are included. The control unit also collects telemetric data on the state of units of the apparatus, entering from the corresponding sensors. These telemetric data are recorded subsequently on tape recorder and are transmitted to earth together with the video signal.

The video signal storage device (Fig. 4.17), together with the television cameras, is the most complicated unit of the onboard television apparatus. There are three videotape recorders in the storage unit, each of which is designed to record 35 frames. Considering that not every orbit passes above a receiving point, two videotape recorders can be turned on in sequence, with a total memory capability of 70 frames. The third videotape recorder is used for the mode of simultaneous recording and reproduction of stored information, when the satellite is located above a receiving point. The direct method of video signal recording, accomplishment of which is connected with incorporation of an original video loop correction device, is used in the videotape recorders (Fig. 4.18). To reduce the time of transmission of the recorded video information (because of the limitation on the time of a communication session of the AES with the receiving point), reproduction is accomplished from the magnetic tape four times more rapidly than recording. The video signal obtained from the tape recorders is supplied to an amplifier, in which additional shaping of it is carried out and, then, to the onboard radio transmitter.

The onboard radio transmitter (Fig. 4.17), with a power of about 15 W, transmits the video signal to the ground stations, within the limits of direct visibility. A ground station is a complicated set of apparatus for receiving, transmitting and processing information. A television signal received by the tracking antenna is demodulated, reproduced on the video monitor screens and is recorded by magnetic or motion picture photographic film, and it then is processed and sent to the meteorological center. /203

Fig. 4.18. Outward appearance of videotape recorder installed in Kosmos-122 satellite.

The first experimental satellites were launched in 1960 in the USA. In the next 10 years, meteorological AES of the Tiros (ten AES), Nimbus (four AES), ESSA (nine AES), ATS (five AES) and ITOS (one AES) type AES were orbited.

Television information, as in the Soviet systems, is transmitted by two types of apparatus: the AVCS (advanced vidicon camera system), an electronic-magnetic system with video information storage for global gathering of it and the APT (automatic picture transmission) for direct image transmission.

The APT type television apparatus is the IDCS (image dissector camera system) apparatus, described in Section 4.2.

Apparatus of both television systems, AVCS and APT are installed in satellites of the ESSA, Nimbus and ITOS series. In distinction from other AES, the Nimbus and ITOS have a triaxial AES orientation and stabilization system. Such a system in the Nimbus-4 AES provides constant orientation relative to the earth, within 1° in each of the three axes.

The ITOS meteorological satellite was launched 11 December 1971 and, receiving the name NOAA-1 (National Oceanic and Atmospheric Administration), had the following composition and apparatus parameters:

1. Direct television image transmission system (APT):
   - -- coverage, 3300 × 2200 km (800 × 600 lines);
   - -- resolution at subsatellite point, 3.2 km;
   - -- number of images obtained in one orbit, 11;
   - -- overlap between neighboring images, 30%;
   - -- single image transmission time, 150 sec;
   - -- line frequency, 4 Hz;
   - -- time between neighboring frames, 260 sec;
   - -- time for photographing 11 successive frames, approximately 48 min.

The video information is transmitted at a frequency of 137.5 (137.62) MHz. The information is received by a network of simplified receiving points. At the present time, there are about 500 such stations in the world.

2. AVCS global television information collection system:
   - -- coverage, 3300 × 3300 km (800 × 800 lines);
   - -- resolution at subsatellite point, 3.2 km;
   - -- number of images obtained in one orbit, 11;
   - -- overlap between neighboring images, 50%;
   - -- single frame readout time, 6 sec; /204
   - -- time between photographs of two neighboring frames, 260 sec;
   - -- time for photographing 11 successive frames, approximately 48 min;
   - -- capacity of magnetic recording device, 38 frames (three orbits around the earth);
   - -- time for reproduction of information obtained in one orbit, less than 2 min. Information is transmitted at a frequency of 1697.5 MHz. Transmitter power is at least 2 W.

3. Scanning radiometer (SR):
   - -- coverage, continuous band in direction of satellite flight, from horizon to horizon (scanning angle, 150°);
   - -- radiometer channels:
     a) in visible range, 0.52-0.73 μm;
     b) in infrared (IR) range, 10.5-12.5 μm;
   - -- resolution at subsatellite point, 3.2 km in visible range, 6.4 km in IR range;
   - -- storage, two magnetic recording devices with capacity of 145 min each.

The scanning radiometer data can be transmitted in the direct transmission mode, for reception at APT stations. The data are transmitted at a frequency of 1697.5 MHz.

4. Plane radiometer for recording outgoing radiation.

5. Solar proton sensor.

Narrow-band, slow-scan cameras, with vidicon type camera tubes, also were used to obtain images of the moon during the flight of the Ranger spacecraft and landing of the Surveyor spacecraft on its surface. They were used in obtaining images of Mars, when the spacecraft made a close flyby of the planet (Mariner-64 and Mariner-69) and from the orbit of the Mars satellite (Mariner-71).

The slow-scan system in the Ranger spacecraft is interesting, due to the fact that it is a combination of a system with high definition and long frame transmission time and a system with low definition, but a short frame transmission time. The idea of building such a system, permitting a changeover from transmission of data on rapid movement of an object to transmission of data on details of an object was formulated as long ago as 1936, by S.I. Katayev [61], and it was put into practice in planning the first "lunik" in the USSR. Of the six cameras of the Ranger spacecraft (Fig. 4.19), four operated with 260 line scanning, at a frame time of 0.2 sec, and two cameras, with 1125 line scanning, at a frame time of 2.5 sec [96]. The video frequency band of each camera was 200 kHz. A 1-inch type JO 3358 vidicon was used in the cameras.

The operation of forced erasure of the residual image included illumination of the photolayer, by means of special lights, located around the vidicon target, and multiple scanning by an electron beam.

The operating cycles of the /205
camera, with readout times of 0.2 and 2.5 sec, were 0.84 and 5.12 sec, respectively. The residual signal after erasure was less than 10%. Signals from the television cameras were amplified and sent to the video commutator, which accomplished sequential transmission of images by two independent channels. The signal in each channel was frequency-modulated and sent to the 60 W transmitter.

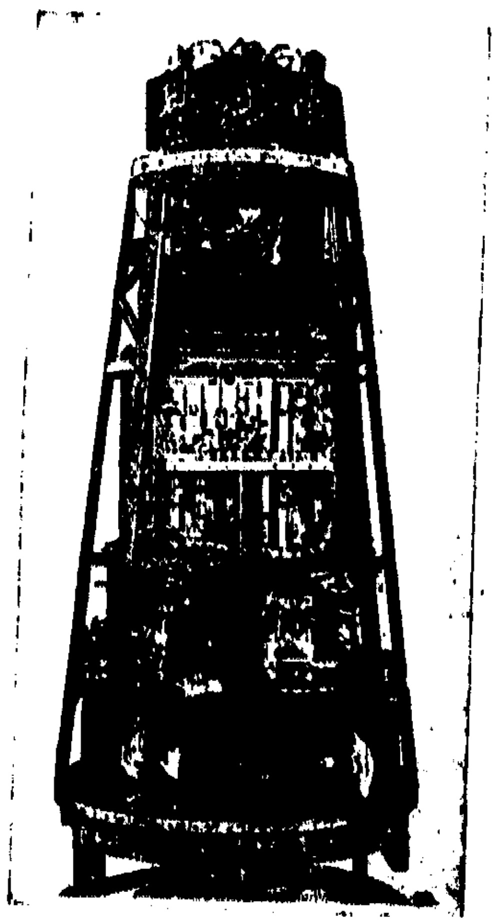


Fig. 4.19. Ranger spacecraft television apparatus.

The slow-scan system of the Surveyor spacecraft was a combination of a system with high and low definition, which, in distinction from the Ranger system, was carried out with one camera [104]. The 1-inch GEC type 1335A2 vidicon camera had two operating modes: with 200 line scanning at a readout time of about 20 sec and with 600 line scanning at a readout time of 1.1 sec. The first mode of operation required a narrow video frequency band of about 1.2 kHz and the second, 200 kHz. Operation of the camera with low definition was carried out in the initial stage, before unfolding of the solar battery panels and high-gain antenna; the camera then was changed over to the high definition mode. The operating cycle of the camera in the first mode was 61.8 sec and 3.6 sec in the second. The remaining time was used for erasure of the vidicon target.

A singularity of the slow-scan system of the Mariner spacecraft [105] was the long time for readout of the relief built up on the vidicon photolayer (24-42 sec), modulation of the vidicon readout beam by a sinusoidal signal, and coding of the video signal. The long readout time was selected, for matching with the rate of input of information in the onboard memory. Modulation of the vidicon readout beam was used, in order to avoid amplifying the video signal, by means of a direct current amplifier and to remove the video signal spectrum from the region of low-frequency noises of the 1/f type. /206

The Mariner system has two television cameras: a camera with a wide-angle lens and a camera with a narrow-angle, telephoto lens, which transmits the central part of the image of the first camera. The frame size on the GEC type 1342-010 vidicon target is 9.6 × 12.5 mm. The number of lines of each camera is about 700 and the readout time of one frame is 42 sec. The cameras operate alternately, with an 84-sec cycle time. The video frequency band is not over 10 kHz. Images obtained from the Mariner-64 spacecraft showed that the surface of Mars has low contrast. To improve signal transmission from the low-contrast objects, the video signal underwent special processing. From the output of the automatic gain control device (AGC), the video signal was sent to an amplifier cascade, the amplitude characteristic of which has the form of a cubic parabola. After amplification and processing, the video signal was sent on two separate channels, analog and digital. In the digital channel, the amplitude of each seventh element of a video signal line was transmitted as 8 bits of data, in which the 2 most important bits of digital video information were transmitted through a telemetry channel. The remaining, less important 6 bits were sent to a digital videotape recorder. In distinction from the digital channel, the analog channel processed all elements of the image for subsequent transmission to an analog videotape recorder. The memory capacity of the digital videotape recorder is $1.8 \cdot 10^8$ bits.

The number of bits per image element was increased from 8 to 9, in the apparatus of the Mariner-71 spacecraft, which is close in design and equipment to the Mariner-69 spacecraft.

The examples of specific apparatus presented above illustrate the broad possibilities of use of electronic slow-scan systems in space research. The high light sensitivity and resolution of such systems, combined with long service life and radiation resistance, make them irreplaceable for investigation of the remote planets.

The prospects of building highly-sensitive electronic slow-scan cameras with high resolution were stated in Chapter 3. Putting these prospects into practice is of importance, not only for improving the systems described above, but for creating new types of systems, for example, holographic slow-scan systems.

It is known that introduction of the holographic method of image reproduction involves requirements for high resolution of the light receivers, close to the Rayleigh diffraction limit. Achievement of this resolution obviously is succeeding, mainly in slow-scan television systems [75, 78].

4.4. Wide-Band Electronic System

The slow-scan television apparatus of orbital meteorological satellites gives quite detailed information on the state of the cloud cover of the earth. In the case of use of satellite systems, it is possible to obtain information on the cloud cover of the entire earth. The dynamics of cloud formations in this case can be observed with definite distinctness. Depending on the number of satellites, their altitudes, coverage of the surface of the earth by television cameras, the distinctness of production of information can be quite high. The necessity for image processing and assembly time determines the delay in use of such information.

Space research technology permits use of a wide-band electronic television system of the broadcast type, for direct observation of extensive regions of the globe, on a real time scale. The first such experiment was carried out, using the Soviet communications satellite Molniya-1 [96]. The satellite orbital parameters permit observation of regions of the globe 6-10,000 km in extent, from altitudes of 20,000-40,000 km. The virtues of such a system consist of the possibility of direct observation of cloud cover, determination of the dynamics of movement of large cloud formations, observation of the development of cyclones, etc. This possibility is of special interest for observation of regions which are most characteristic meteorologically: the circumpolar "weather factories" and the regions of cyclone formation. As an example, a picture of development of a cyclone and anticyclone within single days, obtained by means of the Molniya-1 satellite television apparatus, is presented in Fig. 4.20.

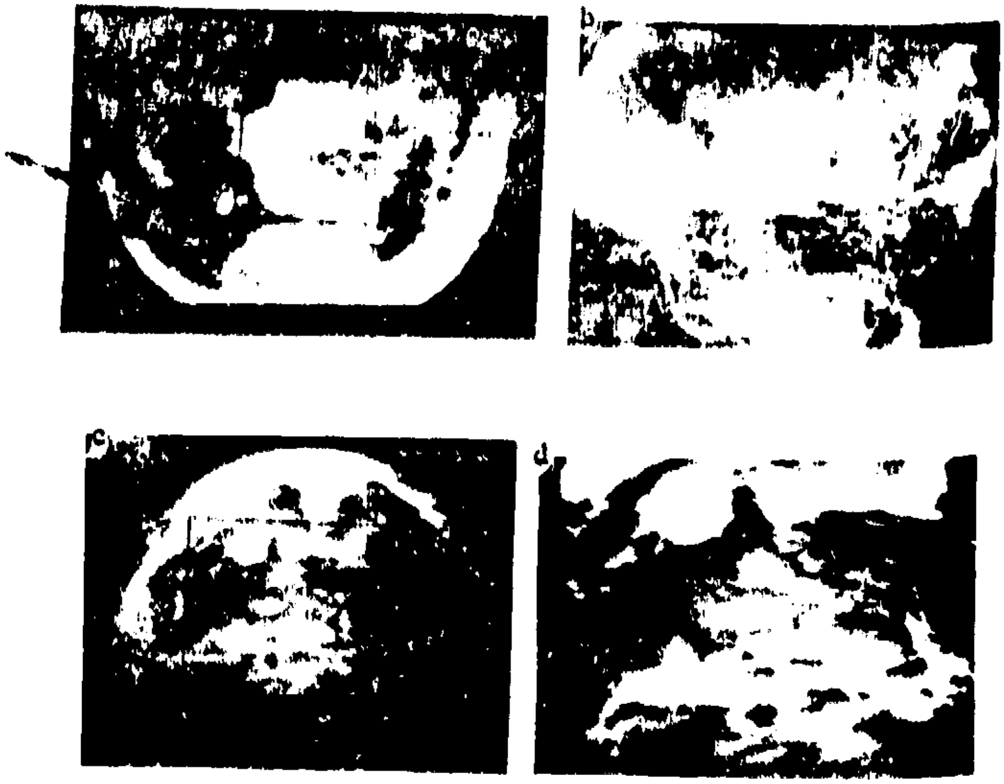


Fig. 4.20. Picture of development of cyclone and anticyclone: a) initial image of cloud formations; b) image of region obtained with long-focus optics; c and d) same formations after 1 day.

The parameters of the television system installed in the Molniya-1 satellite basically correspond to the requirements of the government standard GOST 7845-55. The onboard television apparatus provides observation of the surface of the earth in assigned sections of the orbit, formation of a compete television signal and its transmission to the input of the transmitter of the satellite relay system. Transmission, reception, recording and further relay of the television images are carried out by the official resources of the satellite relay system. This circumstance was the basic approach to use of a selection of standardized scanning parameters, although the task of observation of the meteorological situation from a Molniya-1 type satellite can be solved by a slow-scan system, without magnetic recording of the television data.

The onboard television apparatus of the Molniya-1 satellite contains two identical television cameras, a primary and a reserve (Fig. 4.21). These cameras are equipped with a device, providing for pointing them towards earth, as well as a device for scanning the surface of the earth, using narrow-band optics. /208
Since the camera, containing quite complex optico-mechanical devices, is designed for operation under the conditions of

open space, it is mounted in an air-tight housing and equipped with a two-stage temperature regulating system. To decrease the chamber volume, the necessary minimum of elements are retained in it (Fig. 4.22): two optical lens heads with light filter system 1, electron beam tube with focusing-deflecting system 2, preamplifier 3, tube mode control system 4 and heat regulating device 5. The remaining links of the television apparatus are placed in the television channel unit, located under more favorable physical-climatic conditions, inside the Molniya-1 satellite.

The television channel unit includes (see Fig. 4.22) scanner 6, linear amplifier 7, forming the complete television signal, sync generator 8, control unit 9, power supply unit 10 and frequency modulator 11, converting the television signal spectrum, in accordance with the intermediate frequency of the relay channel, which provides the simplest coupling of the television apparatus with the communications channel. /209

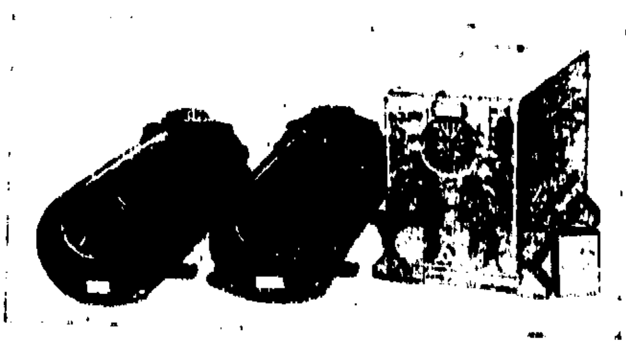


Fig. 4.21. External appearance of onboard television apparatus of Molniya-1 satellite.

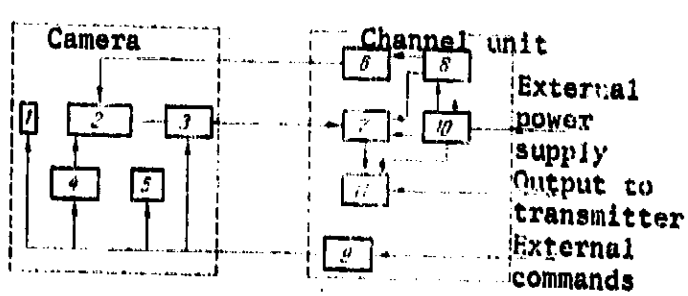


Fig. 4.22. Structural diagram of onboard television apparatus of Molniya-1 satellite.

The camera is equipped with an automatic video channel regulating system, providing for operation over a broad range of light fluxes. The optical head has two lenses, with focal distances of 20 and 50 mm, and a disk with 6 light filters. One of the light filters, providing protection of the vidicon target from burning through by the sun, is automatically set upon switching off the apparatus; the remaining light filters are set by command from earth, and they are used for selection of the optimum light conditions for camera operation and for experimental work.

All circuit elements of the television apparatus are made of semiconductor devices, using micromodule technology. /210

Fig. 4.23. Television photo of earth obtained from medium altitudes.

A television photo of the cloud cover, obtained from the Molniya-1 satellite, is shown in Fig. 4.23.

The resolution of the Molniya-1 satellite television system does not exceed the maximum value determined by use of standard broadcast television. Therefore, the purpose of such a system is to obtain video information on consolidated cloud processes. The reduction in requirements as to resolution, compared with those on a slow-scan meteorological system, and the absence of the necessity for video signal storage devices permit construction of a television system with small dimensions, weight and energy consumption. The economy of such a solution also is determined by the fact that the onboard television apparatus is installed in a standard communications satellite, intended for relay of television programs, without detriment to its purpose. In this case, the satellite radio channel and its official system of ground provisions are used. The energy expenditures also are small, since a 3-5-minute session in the breaks in a television program, repeated 2-3 times a day, are sufficient for accomplishing the task of meteorological observation.

In creating synchronous communications satellite systems, providing global relay of television programs, installation of such simple television apparatus in them solves the problem of simultaneous observation of the cloud cover of almost the entire surface of the globe. It is evident that the television system described above does not replace an orbital meteorological system, but is an effective and economical supplement to it.

The onboard cameras used in the Molniya-1 satellite are a part of a set of cameras, making up a space television system (Chapter 5). Description of them in this chapter reflects the classification of the system by purpose. It is a matter of investigation of processes in space, and not of broadcasting, /211 as in Chap. 5. The videotelemetric functions of television systems, which are caused by introduction of television into the technology of spacecraft flight control, are closer to this purpose. For a television system to be used in manual or automatic control of a spacecraft, it must permit measurement of the coordinates of an observed object, its light characteristics, the mutual position of the spacecraft and the object and the like. Development of videotelemetry systems is connected with perfection of the measurement properties of television systems [96].

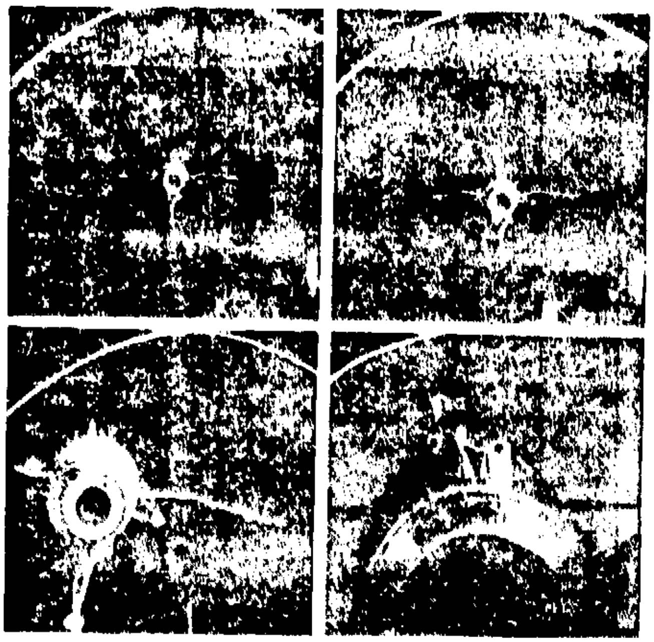


Fig. 4.24. Frames of television transmission illustrating the docking process.

The requirement for carrying out measurements from television images arose with the first steps in development of space television. Thus, distance measurements were carried out in the first space television system for the Luna-3 spacecraft. The inclusion of cross-marks in television images and calibration of television images, by means of the cross-marks and gradation steps, were directed towards improvement /212 of the accuracy of measurement of coordinates and brightness of an object.

An important contribution to development of videotelemetry was a television system for control of docking spacecraft in space. By means of a stereoscopic television device, the possibility of manual docking of spacecraft was provided. The process of spacecraft docking is illustrated in Fig. 4.24 [96].

Necessary conditions for inclusion of television in the spacecraft control circuit are an increase in accuracy of measurement of television images and an optimum combination of automation of the measurement process with visual observations of the astronaut.

Television can fulfill, not only the major function of collection of primary video information in the control process, but such an important function as representation of information from nontelevision sensors and from computers, in the form of images, i.e., in the best form for perception by the astronaut. In this case, even with a very large number of control switching points, the operator aboard a spacecraft can obtain rapid and complete information on the operation of mechanisms and assemblies of the craft. This permits the necessary solutions to be made in time, and with communications with earth, specialists at ground points can monitor the actions of the operator.

5. SPACE TELEVISION SYSTEMS /213

5.1. Coupling Space Television Systems to the Broadcast Television Network

Space research, aside from scientific-technical, has a tremendous social-political importance. Therefore, broadcast television must provide a mass of visual information on the processes of mastering space.

In classification of space television systems by their fields of use (see Section 1.1), space video communications systems, intended for one-way and two-way communications between a spacecraft and the earth, were pointed out. These systems are the space branch of broadcast television, and they are called space television systems. In proportion to the expansion of the scale of penetration of man into space, and especially after creation of permanent, operating orbital and lunar space stations, space television systems will enter the structure of the broadcast television network as regular space television studios. The successes of Soviet television technology, in the field of space research, have permitted an approach right up to solution of the engineering problems of coupling space television systems and, first and foremost, space video communications systems to the broadcasting network. This makes it possible for many millions of television viewers to directly observe the flight of a man under spacecraft conditions, follow the course of the scientific experiments, see planets and television reporting from their surfaces at close range.

The prospects for extensive use of space television systems, for the purposes of broadcasting are imposing a definite technical imprint on their structure and parameters. Designers have to take, not only considerations of system optimization, from the point of view of onboard apparatus, into consideration, but requirements placed by standard television broadcasting. The latter is solved most simply by building onboard television systems, in accordance with the requirements of the All-Union Standard GOST /214 7845-55. However, in this case, it must be taken into consideration that:

-- transmission of the standard spectrum of a television signal places increased requirements on the onboard television transmitter power engineering and the complexity of ground antenna systems, which are not always possible and acceptable;

-- the standard method of broadcasting audio complicates the onboard apparatus and hampers its power engineering;

-- it is inadvisable to use the type of synchronization approved by GOST 7845-55 in a space system, since a considerable part of the dynamic range is used only for transmission of synchronizing pulses; under the severe conditions of operation of space radio channels, this hampers transmission of the video information itself. Moreover, the standard synchronization system complicates the onboard synchronizing devices.

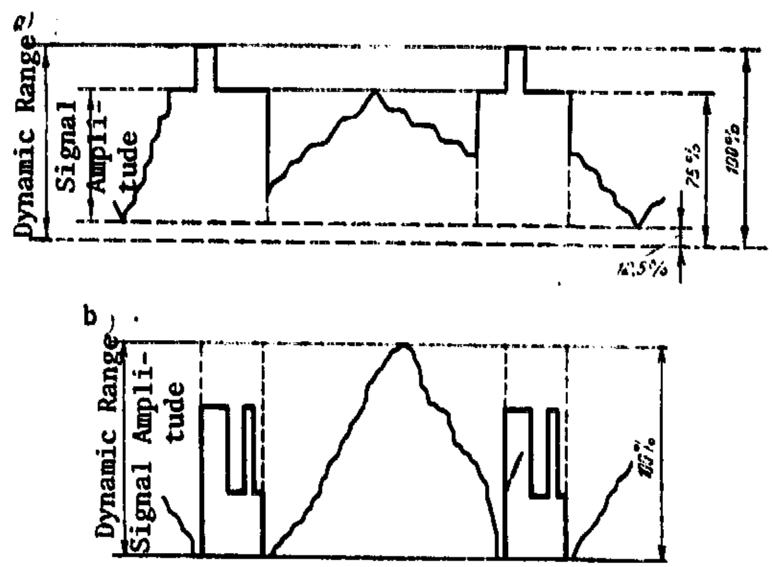


Fig. 5.1. Synchronizing pulse shape: a) according to GOST 7845-55; b) in the form of a code package.

The requirements for energy economy in the onboard radio transmitter forces use of methods of synchronization, in which the sync pulses are transmitted in the form of a code or a packet of sinusoids (sync packets) during the return of the line and frame scanners (Fig. 5.1) [308]. These synchronization methods permit complete use of the dynamic range for video signal transmission.

Also, for the purposes of energy economy aboard a satellite, it is inadvisable to expand the outgoing frequency band for image transmission for audio transmission. Transmission of the /215
audio is possible within the frequency band reserved for image transmission, for example, by means of frequency modulation of the sync packets. An autonomous synchronization mode is obligatory for a space television system. Transmission of supplementary information (for example, telemetry) also is desirable in the structure of the television signal, using a single communications channel.

Consequently, on the one hand, the specifics of operation of the onboard apparatus dictate the necessity for a series of deviations from the regulation of standard GOST 7845-55, in designing onboard television apparatus in a space television system and, on the other hand, a television signal, which completely corresponds to the requirements of this standard, is necessary for relay over the broadcast television network. This contradiction is solved by means of inclusion of special conversion devices in the ground stations, for television signals received from aboard a spacecraft, into a signal provided for by GOST 7845-55. The conversion methods can be diverse, depending on the degree of mismatch of the onboard and standard television signal parameters.

In this manner, a space television system can determine both the set of onboard television devices, communications channel and ground devices which, by means of appropriate transformations,correct the television signal to a form suitable for use in the television broadcasting network and provide for introduction of this signal into the broadcasting network. Brief characteristics of the onboard television apparatus, communications channel and ground space television resources are presented below.

5.2. Onboard Television Apparatus

The onboard apparatus of a television system used in space television serves, not only the purposes of broadcast television, but performance of tasks of an applied and a scientific nature. It forms television images for monitoring the activities of man under spaceship conditions and video communications with earth and between spacecraft, observation of the operation of spacecraft systems and control of them, internal television communications, checking orientation, obtaining information on scientific experiments, biological, physical, astronomical. The majority of these tasks are of indisputable interest for broadcast television. From the point of view of use of television information aboard a spacecraft, the onboard apparatus must be matched to the recipient of the information, man, in the optimum manner and therefore, it can be built according to the principles adopted in broadcast and industrial television. Optimization of one of the important links in a space television system, the communications channel, as has already been noted, makes it necessary to depart from the standards adopted in broadcast television. /216

Onboard television equipment used in space television systems has been developed in several versions:

1. with 100 line scanning, at a frame frequency of 10 frames/sec;

2. with intermediate parameters: 400 lines per frame, at frame rates of 10 and 25 frames/sec;

3. wide-band version, having, in conformance with GOST 7845-55, 625 lines per frame, at a frame rate of 25 frames/sec.

The first version of onboard television equipment was used in 1960 and 1961, in the second space satellite and in the Vostok-1 spacecraft. Reduction in number of lines per frame and frame rate permitted the width of the video signal spectrum to be narrowed to 50 kHz, through deterioration in television image quality. This change in image quality in the frequency band was necessary, for decreasing the power of the onboard radio transmitter. It permitted use of ground antennas of smaller sizes. Moreover, it must be considered that, before 1960, there were no experimental data on radio transmission of wide-band television signals from space.

The requirement for unattended operation of onboard cameras of small sizes predetermined the choice of the vidicon type camera tube. The onboard apparatus of the second space satellite and of the Vostok-1 spacecraft contained two television /217 cameras with LI-23 vidicons, operating in a mode with simultaneous storage and readout processes, similar to the mode of normal ground transmitting cameras. The onboard cameras were equipped with 20 mm focal length lenses.

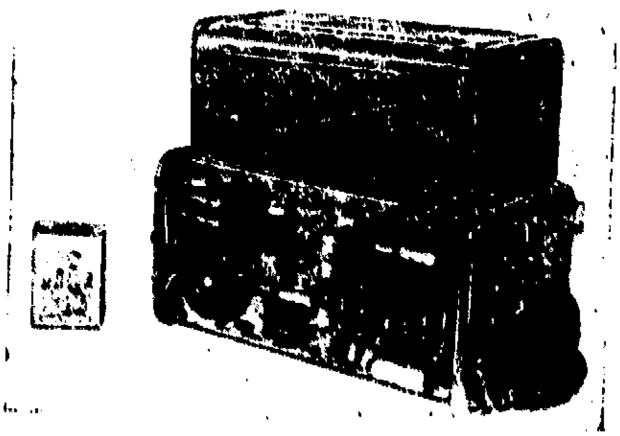


Fig. 5.2. External appearance of onboard television camera installed aboard the second space satellite and in the Vostok-1 spacecraft.

The external appearance of one of the cameras used in the second space satellite and in the Vostok-1 spacecraft is shown in Fig. 5.2. A television photo of the first astronaut Yu.A. Gagarin, obtained by means of this camera, is presented in Fig. 5.3. The line structure is distinctly seen in the photo.

The accumulation of experience in television transmission from space permitted the quality of television

Fig. 5.3. Television photo of first astronaut Yu.A. Gagarin obtained from Vostok-1 spacecraft.

Fig. 5.4. Television photo of spacecraft cabin and astronaut.

monitoring of the condition of the astronauts to be significantly improved in the following spacecraft launches (beginning with the Vostok-2 spacecraft), by means of changing to the second version of onboard television apparatus with 400 lines, at 10 and, then, 25 frames per second.

The onboard television equipment of the Vostok spaceships had two cameras, using type LI-409 vidicons. One of the television cameras provided full face observation of the face of the cosmonaut and the other, the profile. The second camera was equipped with an angular optical head, having a cross sectional view of the rear section of the lens, with a focal distance of 10 mm, and it provided wide coverage of observation of the inner space of the cabin (Fig. 5.4). The camera included a tube, with a focusing-deflecting system, amplifier with 1 V output signal, scanning unit, rectifiers, and onboard /218 power transformer. All links of the camera were made of semiconductor devices. Besides the camera, the onboard apparatus contained a synchronizing device, control device, radio transmitter and illumination system. Special attention was given to development of the illumination system, since the correct choice of illumination showed up decisively in television image quality. Television photos of astronauts, obtained aboard the Vostok spacecraft, by means of a 400 line, 10 frame/sec television system, are shown in Fig. 5.5.

A hermetically sealed shutter camera, operating under /219 open space conditions, was used on the Voskhod-2 spacecraft. The extravehicular activity of astronaut A.A. Leonov was observed by means of this camera (Fig. 5.6).

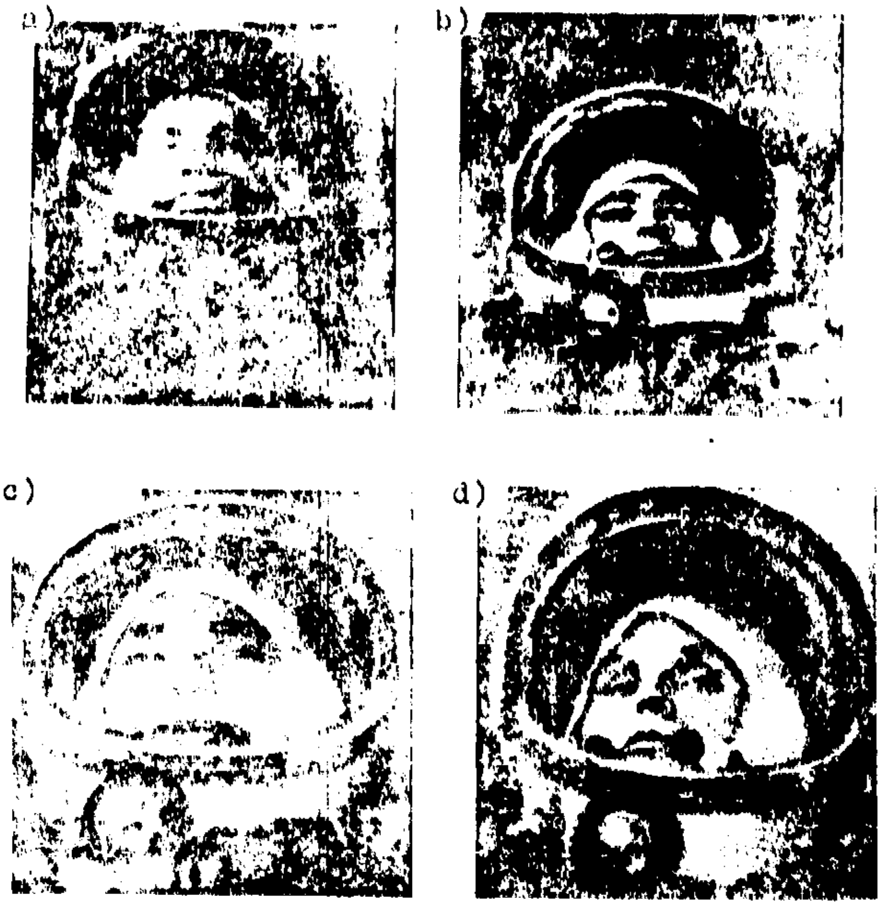


Fig. 5.5. Television photos of astronauts obtained from spacecraft: a) P.R. Popovich; b) A.G. Nikolayev; c) V.F. Bykovskiy; d) V.V. Tereshkova.

Fig. 5.6. Television photo obtained from Voskhod-2 spacecraft; astronaut A.A. Leonov in space against the background of an image of the earth.

The television photos presented give a graphic idea of the dynamics of development of quality of television images taken from aboard spacecraft. This development was accomplished, both as a way of improving the apparatus characteristics and improving the illumination conditions of its operation.

The experience accumulated permitted a system to be tested on satellites of the Kosmos series, constructed according to standard parameters: frame rate, 25 Hz, 625 lines. On the Soyuz spacecraft and, then, on the

Salyut spacecraft, the standard television system was officially used. It contained a system of internal and external cameras (Fig. 5.7). The number of cameras can be varied, depending on the task [96].

Fig. 5.7. Astronaut Ye.V. Khrunov.

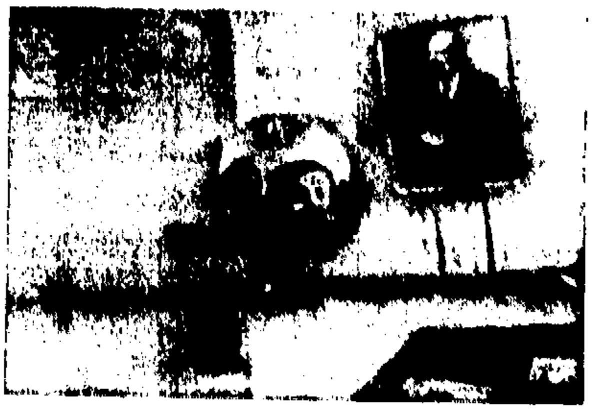


Fig. 5.8. Astronaut B.V. Volynov (seen in mirror) carries out television reporting from the orbital section of a Soyuz spacecraft.

A well-worked-out system of illumination and the availability of a video monitor, permitting the astronaut to monitor information transmitted from onboard, provided high quality reporting from aboard (Figs. 5.8, 5.9). Construction of the system by standard parameters and elimination of image rerecording sharply increased the quality of information supplied to the broadcasting network.

The use of wide-field television systems with standard parameters does not eliminate the use of systems with a reduced number of lines and frames.

An increase in the /220
distance during flight to other planets, at the contemporary level of development of communications channels, requires further narrowing of the television signal spectrum. This aggravates the problem of optimum matching of the television signal spectrum with the throughput capacity of the communications channel.

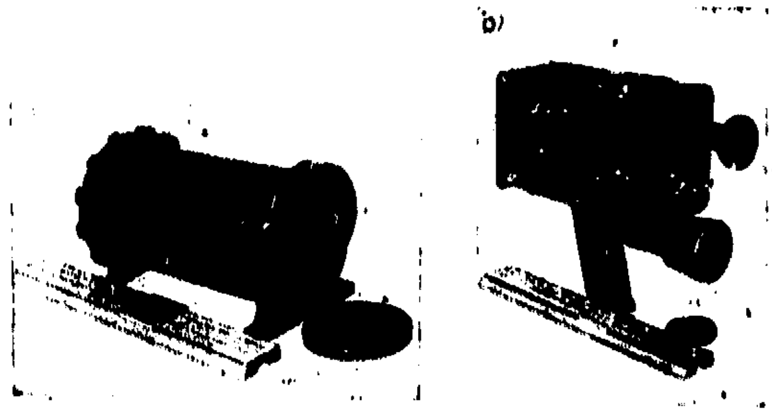


Fig. 5.9. Space television cameras with standard scanning parameters.

5.3. Methods of Matching Signal Spectrum with Communications Channel Transmission Band /221

The communications channel requirements are determined by the television system parameters: the amount of information, the necessary rate of transmission of it, the assigned qualitative characteristics of the television image, requirements on authenticity of data transmission. The possibility of communications channels, radio channels, used at the present time, are limited by a number of factors.

A characteristic of space television system radio channels is the wide range of distances, to which communications must be provided, from hundreds to hundreds of millions of kilometers. The communications distance H_l is determined by the parameters of the radio channel elements:

$$H_l = \frac{\lambda}{4\pi} \sqrt{\frac{P_{tr} G_{ta} G_{ra}}{kTFq}}.$$

As follows from the formula, the communications distance depends on wavelength λ, transmitter power P_{tr}, the transmitting antenna gain G_{ta}, the receiving antenna gain G_{ra}, the noise temperature of the system T, transmission band F, signal-noise ratio at the receiver output q, and the Boltzmann constant k. It would seem that, with this number of variable parameters, it would be easy to create a communications channel, having the characteristics necessary for any television system. Practically, the selection of radio channel parameters is limited by engineering solutions, which are actually achievable and the technical and economic advisability.

Space noises absorbed in the ionosphere and troposphere affect the choice of range of λ. Figure 5.10 illustrates the quantitative effect of these factors. Besides the widely distributed galactic noises indicated on the graph, having a maximum in the plane of the ecliptic and a minimum in the region of the galactic poles, the radiation of interstellar hydrogen at a frequency of about 1.43 GHz and the large number of discrete radiation sources should be taken into consideration. With sharply directed ground antennas, the probability of serious interference on the part of the discrete sources, which have small angular dimensions, is insignificant. The sun is an exception; its rays, entering the antenna direction pattern, blind the receiving point. Ionospheric absorption, which is insignificant in the high frequency region, increases quadratically with decrease in frequency, and it shows up perceptibly in the range below 100 MHz.

Losses take place in this range, owing to rotation of the polarization plane in passage of the waves through the ionosphere.

Tropospheric absorption depends on the reception angle, i.e., on the path length of the radio beam in the troposphere, concentrations of oxygen and water vapor and precipitation. By virtue of these causes, the troposphere is practically opaque to frequencies above 10 GHz. The dependence of absorption on frequency also is shown in Fig. 5.10. Thus, from the point of view of the factors being considered, frequencies below 0.1-0.3 and above 10 GHz are practically excluded. In this case, the 4-6 GHz range should be considered to be the optimum. /222

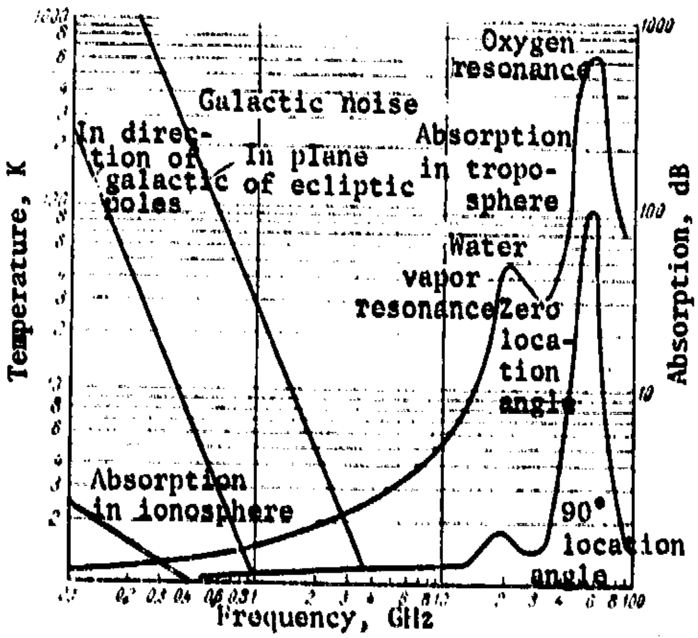


Fig. 5.10. Galactic noise and atmospheric absorption vs. frequency.

However, the choice of the optimum radio channel frequency range also is determined by a number of engineering considerations, transmitter efficiency, the possibility of building onboard directional antennas, dimensions and weight of apparatus, etc. Therefore, deviations from the optimum ranges can be encountered in practice. For low-flying orbital satellites, in which principally the troposphere interferes, the meter range can be used, providing good transmitter efficiency and operations by nondirectional antennas. At medium distances, with a nondirectional or low-directional antenna, the decimeter channel can be used and, at long ranges, where the use of sharply directed transmitting antennas is inescapable, the centimeter range.

An increase in gain of onboard antennas, under otherwise equal conditions, sharply reduces the requirements for onboard transmitter power. However, this requires orientation of the carrier at the time of the communications session, and it is achieved by means of design complications in the antenna, increasing its dimensions and weight. Moreover, in increasing the antenna gain, the radiation angle is constricted, which leads to the necessity for use of complicated antenna directing devices and, ultimately, to increase in weight and energy consumed. /223

Increasing the gain of ground antennas is achieved by increasing their effective (and geometrical) areas and by the accompanying constriction of the directional pattern. Ultimately, this leads to an increase in dimensions, weight and wind load of the antenna, to increase in tracking drive power and, as a result, to an increase in cost of antenna equipment.

The maximum achievable receiver noise temperature in use of quantum mechanical and cooled parametric amplifiers is 8-20°K. However, allowing for antenna device noise, space noise, etc., the actual effective noise temperature of a receiver can reach 70-300°K.

Graphs, illustrating the interconnection between transmission frequency band and communications distance, at various radio transmitter power values, effective antenna area and receiver sensitivity, are presented in Fig. 5.11a. /224

The graphs were obtained at effective receiving antenna areas of 35 m^2 (curves 1, 2, 3) and 200 m^2 (curves 4, 5, 6). The noise temperature of the receiving system was 300 K (curves 1, 2, 3) and 70 K (curves 4, 5, 6).

Thus, in optimization of space television systems on the whole, a reasonable compromise must be found between the requirements placed on the communication channel, the tasks of television transmission and its actual resources. The problem of matching the signal spectrum with the transmission channel band is solved in two directions:

1. matching the television signal spectrum with the transmission channel band, at a given power of the latter;

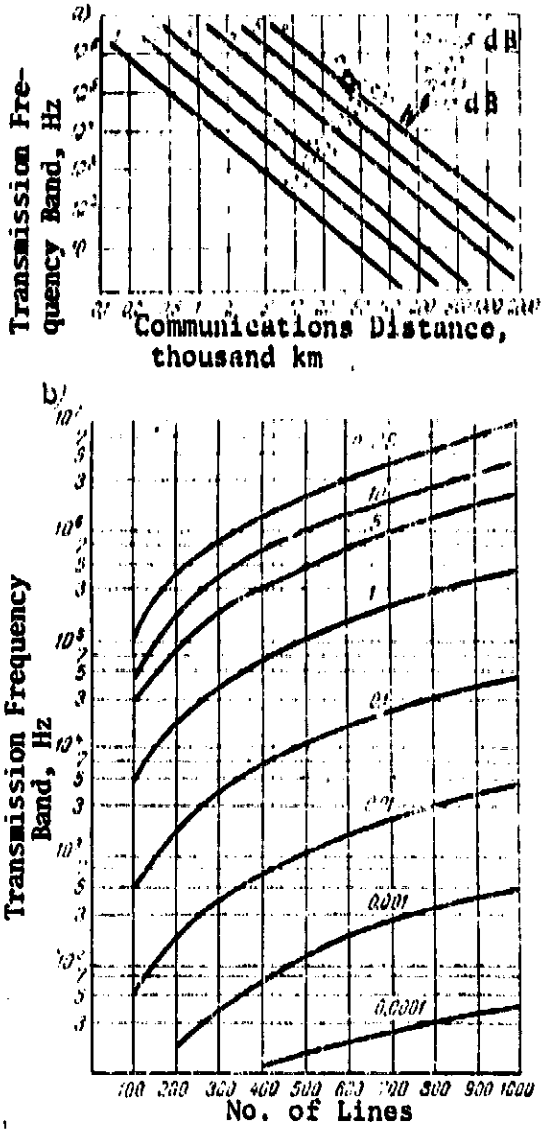


Fig. 5.11. Calculated graphs: a) Frequency transmission band vs. communications distance in frequency-modulated channel; b) transmission band F_e vs. number of lines z and frame rate n; G - transmitting antenna gain; q - signal-noise ratio; m - modulation index; b - coefficient of losses unaccounted for.

2. time matching of the signal with the channel.

The latter is caused by the fact that space radio channels, practically, cannot provide continuous communications at any time.

For objects in earth orbit, the zone of communication with one receiving point is limited by the radio horizon and, the possible communications time changes from several minutes to several hours, depending on the altitude of the satellite. For distant space objects, communications sessions are time-limited by the rotation of the earth and in duration, by the storage of energy aboard the spacecraft. Matching the television signal spectrum with the transmission channel band is most effectively solved by selection of the scanning parameters, providing the necessary signal spectrum. The graph (Fig. 5.11 b) gives a visual idea of the approximate ratio between the transmission frequency band F_e and the scanning parameters: frame rate n and number of lines per frame z.[1]

However, freedom of choice of scanning parameters frequently is limited by the nature of the subjects being transmitted, their

[1]The calculation was performed by the formula $F_e = 0.4\ nz^2$.

dynamics, etc. Selection of scanning parameters also is limited by the characteristics of the television camera tubes. The ideal tube for this task should have a short image memory time, with the possibility of complete readout of an accumulated relief in one cycle (one frame), over a wide range of readout rates. Actual tubes frequently do not meet these requirements.

In the case when from the conditions of use of a television system, the problem of matching it to the communications channel is impossible to solve by selection of scanning parameters, intermediate rerecording of the image or signal is used. In this case, recording of the image (signal) is performed, with digitization determined by the operating conditions of the television system, and the transmission is carried out at a rate, which transforms the signal spectrum to values matching the channel. /225

Intermediate image recording without transformation into a signal can be accomplished on photographic film, electrostatic film, tubes with tape targets, and by thermoplastic methods. Intermediate signal recording is provided by means of magnetic recording, storage tubes and others. Phototelevision systems (Luna-3, Zond-3, Luna-12) and systems with intermediate signal recording on magnetic tape (Kosmos-122) have found practical use. Systems with intermediate image memory theoretically have high characteristics: high recording density, the absence of supplementary signal transformations. However, higher reliability of the magnetic recording system under space conditions and the simplicity of transformation of the spectra in them, by means of change in the carrier rate facilitates their prospects.

The necessity for rerecording television data aboard a satellite also arises in those cases, when, besides transmission by a narrow-band channel, television information has to be used in the satellite itself (for purposes of automatic image analysis or visual observation by the operator). In transmission of a changing subject, magnetic or electronic rerecording can be used.

In transmission of stationary images, pulse transformation is possible. In this case, image scanning is performed at the necessary rate, and signal spectrum compression is provided by strobing one element of each line with a pulse, shifted by one element in each succeeding frame. Only the first elements of all the lines will be extracted in the first frame, the second elements in the second, etc. These short pulses are extended to the length of a line (while retaining their amplitudes) and, in this manner, one "slow" frame is formed from n "fast" frames, with a spectrum n times less than the initial one.

Matching television systems with communications channels in time is accomplished, by means of the systems described above, with intermediate recording of television data. In the general case, for time matching, transformation of the signal spectrum is not required. Sometimes, the short length of a communications session, besides a time shift in data transmission, requires rapid dumping of the entire volume of recorded data in a limited time. For example, in the television system of an orbital meteorological satellite, information storage for a period of an orbit (1-1.5 hours) should be dumped in the time of communication with a ground point (5-6 min). This problem is solved most successfully in systems with magnetic recording, by means of spectrum transformation, providing accelerated transmission with compound spectrum expansion.

In conclusion, it should be noted that development of quantum electronics, putting the question of use of laser channels for communications between space objects and the earth on the agenda, will permit again approaching the problem of coupling television systems to the communications channels in the very near future, removes a number of limitations, which apparently will increase the qualitative characteristics of space television systems and enlarge the group of problems, which can be solved by it. /226

5.4. Features of Construction of Space Television System Ground Station

The purpose of the ground television resources in a space television system is reception of onboard signals, monitoring the images and audio received, recording them, transformation into standard form, transmission over communications lines to the central television network and, further, with the official resources of the television broadcasting network, to the network of the Soviet Union and to foreign countries. The most specific link in ground television resources is a television receiving station, directly receiving information from aboard a spacecraft.

A ground station (Fig. 5.12) includes an antenna with guidance system, radio receiver, device for visual operational monitoring of signals received, image and audio quality control, audio extraction, synchronization, image and audio recording apparatus, system for conversion of signal to standard form, /227
relay line output devices and a number of auxiliary devices: monitoring-test set, voltage regulators, operational photographic material development unit, official signaling and communications system, and video output monitors.

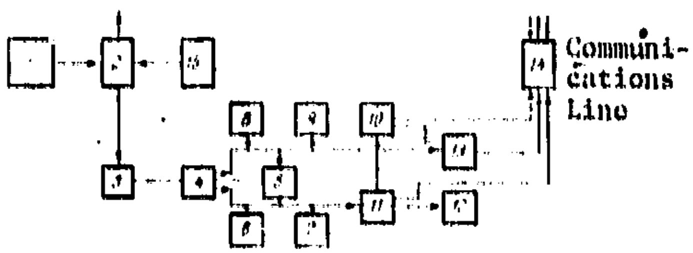


Fig. 5.12. Structural diagram of ground station (second half-set of apparatus not shown): 1 - antenna with guidance system; 2 - control panel; 3 - radio receiver; 4 - signal amplifier-distributor; 5 - sync set; 6 - oscillograph; 7 - video monitor; 8 - individual frame photographic recorder; 9 - motion picture recorder; 10 - videotape recorder; 11 - audio extraction device; 12 - synchronous magnetic tape recorder; 13 - video signal transformation and regeneration; 14 - communications line transmitting apparatus; 15 - station self-testing apparatus.

To provide station reliability, its basic elements are duplicated, and they are used in operation in the hot reserve mode.

The great value of television information received from space requires reliable recording of video information, by means of duplicating it, both by number of recording channels and by the methods used. Television information is recorded on motion picture film, by means of motion picture recording devices, providing frame-by-frame photography from the picture tube screen. It is desirable that recording be carried out simultaneously on two motion picture recorders. This makes it possible to make both a positive and a negative record and, moreover, creates a guarantee, in the case of reduction in quality of one of the films in development. The audio is recorded on a synchronous magnetic tape recorder.

Television images and audio are recorded, moreover, on a videotape recorder, which provides the possibility of timely examination of information, as well as secondary processing, intended for regeneration of video information, in the presence of a signal-noise ratio, which is unacceptably low for motion picture recording. For the purpose of testing the station during its operation, as well as for providing rapid information on the most interesting subjects, a photographic recording device is provided in the station set, which permits selective recording of individual frames.

As has already been noted, the station set includes apparatus for transformation of the signals received into a form, corresponding to GOST 7845-55. The composition and complexity of this apparatus is determined by the extent of difference between the onboard signal and the standard one. Image rerecording is necessary, with a difference between the scanning parameters of the onboard television apparatus and the standard. In general form, the task of conversion of television images with different scanning parameters is similar to the task of coupling television broadcasting systems with different standards. These problems have been studied most completely in work [109].

A characteristic of coupling space television systems with the broadcasting network is the considerably greater difference in time relationships of the initial and resulting images. Any image is discrete in time structure, with digitization by elements, lines and frames, in the general case. The method and parameters of digitization are determined by the scanning parameters and readout method selected. The task of rerecording, thus, is reduced to replacement of the digitization parameters of an image received from aboard a space object, by the parameters of the television broadcasting standard. Depending on the conversion method, a signal can be converted both directly, without visualization of the image, and with transition through a visible image. The final task in both cases is transformation of an image, described by the function $F(x, y, T)$, which characterizes the brightness distribution with frame time T, into a new image, which can be described by the function $F(x, y, T_1)$, where T_1 is the frame time of the television broadcasting system. /228

A converter consists of the source of the initial signal, a filter-converter, memorizing the signal (image), a device reading out the signal (image) in the broadcasting standard parameters and a system for forming a signal of standard form. An idealized converter should have a П-shape characteristic, i.e., applied to image rerecording, it should provide uniform memory of the frame of an image in time $T + T_1$, with complete (without residual signal) readout in time T_1. Actual converters do not always satisfy this requirement.

Practically, this conversion can be performed in the following versions.

1. Rerecording of electrical signals in storage tubes (potentialoscope, grafekon). A large residual signal, requiring a special target preparation cycle, and unsatisfactory shading characteristics of such tubes limit their use to the partial cases of rerecording slightly shaded images in a long frame.

2. Magnetic rerecording of electrical signals. Such rerecording theoretically provides high conversion quality; however, it requires interlaced scanning in the onboard system, which narrows the possibilities of use of this type of converter for space television purposes.

3. Image rerecording, using intermediate photography. The initial image is recorded on photographic film, which is developed photochemically, and the photographic image obtained is read out, by means of a standard television channel. Such a rerecording system provides high image quality, but, as a consequence of the considerable development time, the films can be used only for systems in which the long time of the initial frame permits a time shift, determined by the photographic film development period.

4. Image rerecording, by means of an optically coupled picture tube, on which the image is reproduced in the onboard television system parameters, and a television camera tube, operating at the standard scanning parameters.

In the latter version, with a long frame time, skiatron type receiving tubes and tubes with long persistence can be used; with a frame time close to standard, picture tubes of the normal type are used, with increased resolution, increased /229 brightness and a flat screen. In this case, depending on the frame rate of the onboard system, picture tube persistence and readout tube response are selected, which form in combination, a total conversion characteristic, which is close to П-shaped. A conversion system has been fabricated in this version, for broadcasting direct television transmissions from aboard Soviet spacecraft. With ten-frame rerecording, a combination was used, of a picture tube with willemite luminophores, having persistence on the order of 1/20 sec, and a LI-408 vidicon, with somewhat increased response. 25-frame rerecording was performed by a combination of a picture tube with ZnOZn luminophores and a LI-409 vidicon, with decreased response. These combinations permitted practical elimination of flickering, determined by the reduced frame rate of the initial image, with minimum losses in image quality. However, quality reduction is inescapable in any type of conversion, as a consequence of summation of the distortions, arising in individual links of the circuit. In essence, a conversion system is a series coupling of two television systems, to one extent or another, with inescapable superposition of discrete raster structures, and with summation of the amplitude, frequency and phase distortions.

Standardization of an onboard signal having scanning parameters corresponding to GOST 7845-55 and differing only in form of the complete television signal is provided by a sync mix regeneration device. The video signal in a signal received is separated from the sync packet and audio. The ground sync set operates in the driven mode from the onboard line sync pulses. The formed standard sync mix, synchronized with the onboard signal, and the video signal enter an amplifier-regenerator, at the output of which, a complete television signal of standard form is formed. Filters and correcters, permitting improvement in video signal quality, are provided in the regeneration device.

Cable or radio relay lines of the standard type are used as communications lines between the ground station and the television broadcasting network. As a rule, signals enter the television broadcasting network through the television center nearest to the ground station and, further, by the intercity broadcasting network, the Moscow television center (MTC). A special apparatus is provided at the MTC, in which monitoring of images entering from all directions, their repeated regeneration, centralized recording and switching to the output channels are provided. The signals are supplied to the television broadcasting network by the Intervision and Eurovision systems, by means of the official resources of the broadcasting complex, by the usual system.

5.5. Features of Construction of a Space Color Television System /230

General Information

With the development of space television technology and expansion of the fields of use of television apparatus in space, the need has arisen for supplementary information, on the color of the objects being studied and on the spectral composition of the radiation of celestial objects.

Solution of the problem has led to creation of a number of space color television systems (SCTVS), which considerably increases the amount of information obtainable in carrying out a variety of investigations and observations in space disclosing new possibilities, which cannot be achieved by monochromatic television resources.

SCTVS known at the present time, independently of their purpose, have a number of characteristic features, which radically distinguish them from color broadcast systems.

In developing apparatus for television broadcasting systems, the main attention is given to problems of simplifying the circuits and construction of the receivers, which must be as convenient as possible to control and have a cost within reach.

All these requirements are satisfied, mainly by means of making the transmitting apparatus more complicated, by increasing the height of transmitting antennas, increasing the power of television center radio transmitters and incorporating pre-correction signals in the standard color television signal radiated into space.

The principles used in creating individual elements of SCTVS are diametrically opposed. The principal attention in development of the equipment of subsystems is given to reduction in weight, decreasing dimensions and power consumed by the entire set of onboard apparatus, including a color television camera, television signal radio transmitter, transmitting antenna and other auxiliary apparatus.

All elements of this apparatus must be highly-stable and adaptable to prolonged operation without adjustment and without an operator, as well as for remote control from earth.

At the same time, the entire set of ground SCTVS apparatus, including radio receiving devices, signal storage devices, conversion of standards, monitoring-measuring apparatus and other equipment, must have the highest parameters, for achievement of which, considerable complication of any of its links is permissible.

Still another feature of SCTVS is that there are no requirements on it for compatibility with monochromatic and color broadcast television systems, since color image signals in space /231 systems are transmitted by special radio channels.

This circumstance permits use of any method of coding and modulation and arbitrary choice of the time for transmission of one frame, in construction of SCTVS apparatus, based on the actual conditions of operation of the apparatus and the nature of the subjects transmitted.

Of course, the possibility is not excluded here, in case of need, of carrying out subsequent processing of signals received and transformation of them to standard color television signals, which subsequently may be transmitted over the broadcasting network.

The distinguishing features presented concern directly those SCTVS, which are used at the present time, or which may be brought into being in the coming years.

Relay SCTVS have other distinctive features. In such systems, powerful radio transmitters, installed aboard three satellites, stationary with respect to the earth, and located at equal distances apart in synchronous, circular orbits, will send color television signals to earth, which were transmitted beforehand from earth to one of the synchronous satellites, by a special radio channel. The signals of the space radio transmitters, radiating into space at the frequencies of standard television channels, will be received at practically any point on earth by regular television receivers.

It is completely obvious that this type of SCTVS must fully satisfy the requirements for compatibility with the television broadcasting system.

SCTVS can be divided into three main groups, according to the principles of construction, methods of shaping signals and the nature of the tasks performed. The first group includes slow-scan SCTVS, intended for transmission from space of color images of moving objects in a narrow frequency band. This may be an image of the lunar landscape, the surface of the earth or of other planets, transmitted from orbital satellites or spacecraft. Slow-scan SCTVS also are used in satellite meteorology, in study of the cloud cover of the earth, determination of its altitude and tracking its movement. The second group of SCTVS includes phototelevision systems, making it possible to conduct detailed studies and mapping of the surface of the earth from aboard orbital satellites.

SCTVS. by means of which color images of moving objects and rapidly changing subjects are transmitted from space, should be segregated into a separate, third group. The necessity for use of such systems arises in those cases, when, /232
for example, the dynamics of movement of an astronaut, reporting on changes in the lunar landscape during movements of the Lunakhod or the start of a lunar module from the surface of the moon is required.

Slow-Scan SCTVS and Their Use

In designing slow-scan SCTVS, the communications channel frequency band is the decisive factor.

Rigid limitations, with respect to dimensions, mass and power consumption by onboard apparatus decreases the possibilities of construction of sufficiently effective radio transmitters in space and, thereby, the building of wide-band, interference-free space communications channels is hampered. The slow-scan method permits a large volume of information to be transmitted over a narrow-band communications channel. The simplest color television systems made by this method are based on sequential transmission of the signals of alternating frames of color-indexed images. In such systems, the visible spectrum of light radiation usually is divided into three separate sections, and the signals of the red, green and blue color-indexed images are transmitted sequentially, striving for colorimetric similarity of the reproduced image.

In some varieties of slow-scan color television systems, having the name "spectrozonal systems," the task is to detect details of the object being investigated, in the greatest possible detail and clarity. At the same time, a natural reproduction of colored surfaces in their natural colors is not necessary in these systems. Therefore, in "spectrozonal systems," in distinction from color systems for other purposes, the light spectrum, usually going beyond the limits of the visible spectrum, in the direction of infrared radiation, is separated into a large number of narrow spectral zones. Correspondingly, the number of alternating color frames and the number of color-indexed images transmitted increases.

For reproduction of color images transmitted, the signals of the sequential color-index frames are recorded on disk video recorders, after which, simultaneously, the recorded signals are read out at the required rate and they are examined on the screen of a color video monitor. If detailed and prolonged analysis of color photos transmitted and duplication of them is required, the signals of the color images, transmitted at half-frame (field) frequencies, are recorded on black-white photographic film at the receiving point and multicolor prints are then produced on paper, by the polarographic printing method or by the color photography method.

Slow-scan SCTVS was first used on 7 June 1967, for transmission from space of a color image of the earth, from an altitude of 30,000 km. The color television apparatus used in this case, made according to the principle of sequential transmission of color-indexed images, was installed aboard the /233 Molniya-1 orbital earth satellite. This installation included two television cameras (see Section 4.4), with vidicon type tubes. The cameras, designed for operation under the conditions of open space, were mounted in hermetically sealed containers and installed in a device, providing for pointing them at the required section of the earth. A rotating disk with three light filters, red, blue and green, was installed in front of the camera lens, the positions of which were changed by command from the earth. Exchange of all three color filters was accomplished in a time, during which the position of the viewfinder axis was practically unchanged, with respect to the earth. In carrying out the experiment described, synthesis of the color image was accomplished from the three color-indexed images, recorded on photographic film, by the polarographic printing method [110].

Somewhat later, in November 1967, color images of the earth also were obtained, by means of an apparatus operating according to the principle of sequential transmission of color-index frames, installed aboard the American ATS-3 stationary earth satellite.

Earth image scanning in this apparatus was carried out in the direction of the frame, because of the rotation of the satellite (100 rpm) and, in the direction of the lines, by means of a screw mechanism, operating from signals of a solar sensor. In this case, each turn of the screw corresponded to scanning one line of the image.

Sequential transmission of the color frames was carried out through blue, green and red color filters.

The apparatus described made it possible to obtain high-quality color photos of the cloud cover of the earth, which confirmed the extensive capabilities of SCTVS, from the point of view of their use in satellite meteorology, for the purposes of compiling long-range weather forecasts [103].

Sequential transmission of color frames was also used in the flight of the American Surveyor spacecraft, to obtain color images of the surface of the moon. Two spaced color television cameras were installed in the lunar module of this spacecraft, which made a soft landing on the surface of the moon; by means of them, stereoscopic color images of the lunar landscape were transmitted to the earth.

The two cameras transmitted images with different scanning parameters: in use of the narrow-beam transmitting antenna, 600 lines per frame per second and, with omnidirectional radiation, 200 lines and a frame per 20 seconds. A disk with four light filters, red, green, blue and transparent, was mounted ahead of the camera lens. Selection of the scanning parameters and control of the light filter positions was executed, by command transmitted from the ground flight control point. /234

Color images were obtained on the earth, by means of sequential recording of the color-indexed images on photographic film and their subsequent blending by color photography [104].

Further improvement in the equipment of slow-scan SCTVS was produced in the set of onboard apparatus of the Mariner-7 spacecraft, which transmitted color images of the surface of Mars from Mars orbit to the earth, with a definition of 704 lines.

The equipment used in obtaining color television images of Mars contained two vidicon cameras, operating alternately. The cameras had lenses with different fields of view, and they operated with different sets of interchangeable light filters. The entire image signal shaping cycle of one frame of the color image took 42.24 sec. The information obtained was recorded in a magnetic memory in digital form, and it was transmitted to the earth over a channel with a narrow frequency band [105].

A similar, somewhat improved apparatus was successfully used in 1971, during the Mars flyaround of the Mariner-9 spacecraft.

Phototelevision SCTVS

In those cases when the surface of the moon, earth or other planet must be studied in detail and an idea of the relative locations, configurations and spectral characteristics of different small formations and objects is obtained, there must be SCTVS with high resolution, operating with a change in time scale.

The task may prove to be still more complicated, if the object of study turns out to be a moving object.

The solution of the problem is to use phototelevision SCTVS, in which the image of the terrain being studied is registered on the light-sensitive surface of a color photographic film in a brief exposure or, in repeated exposure through appropriate color filters on the surface of black-white photographic film. After appropriate processing, the developed image is scanned in a high-resolution readout device, operating by the traveling beam method, and simultaneous or sequential signals of color-indexed images are formed, which are transmitted to the earth over a narrow-band channel.

Operating on this principle, a phototelevision apparatus with high resolution, achieved as a result of scanning color photographic film with a laser beam, is used at the present time in the American satellite color television systems [111]. /235

Multi-Frame SCTVS

The principal condition which must be satisfied by visual SCTVS, intended for transmission of color images of rapidly changing subjects from space, is that the color-indexed frame sequence frequency in them must exceed a critical frequency, at which smoothness of the transmitted movement is achieved.

The equipment of an onboard set of this equipment must be, not only light, compact and economical, but adaptable for operation under conditions of high vacuum and broad temperature jumps, high accelerations and vibration, and an unattended mode of operation and the possibility of remote control must be provided for in them.

Besides what has been said, it must also be considered that the onboard color television camera should have nonuniform parameters, under different operating conditions. Since the cameras, by means of which a color image of astronauts inside the cabin of an orbital satellite will be transmitted to earth, will have to operate under limited illumination, they should have high sensitivity. Output signals of such a camera will be transmitted a comparatively short distance and, correspondingly, the radio channel used for this purpose can be made with a quite wide frequency band, comparable to the band of a standard television broadcasting channel, with modern technological resources. At the same time, a remote space camera, planned for transmission of color images from the surface of the moon, will operate under intense sunlight during the "lunar day."

Because of the small dimensions, weight and power consumption of the lunar spacecraft and its significant distance from the earth, under insufficiently favorable conditions (imprecise orientation of the antenna and high interference level), the radio channel frequency band should not exceed 2-2.5 MHz. Thus, the task of obtaining color images of rapidly changing subjects from space is solved, either by means of creation of a single, general-purpose, onboard color camera, adapted for operation under the most diverse conditions, or by means of two cameras which differ from each other, each of which is intended for fully specified tasks.

Proceeding to reporting on promising methods of construction of onboard color television cameras, we should dwell, first of all, on the possibility of use in these cameras of the basic principles, on which broadcast and applied color television cameras are based.

In color television broadcasting, three-tube cameras are /236
practically universally used at the present time, one of which is used to obtain a broad-band brightness signal and, by means of the other two, narrow-band color-index signals are formed.

In recent years, new, 1-inch, plumbicon camera tubes have appeared, which has permitted creation of a simplified three-tube color camera, of negligible dimensions and low weight [112].

However, three-tube color cameras are provin., to be sensitive to temperature changes, and there has been no success in simultaneously obtaining all the high parameters which a color television camera intended for operations under space conditions must satisfy.

For reporting purposes and for operation in applied television installations, simplified color television cameras, made of one camera tube, operating in combination with a lined, color-dividing filter, are used.

Such cameras, which differ from normal black-white television cameras by the presence of a lined light filter, can be made very compact and light and, from this point of view, they can be considered to be promising for operations in space. Let us examine the question of the possibility of use of these cameras in greater detail.

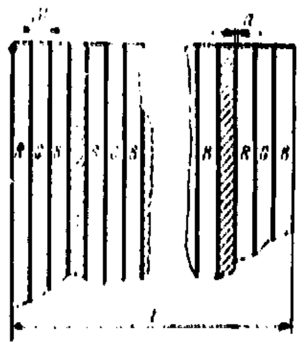


Fig. 5.13. Structure of lined light filter of color television camera with time scanning of signals.

Two types of single-tube cameras with lined light filters have already been built. In one of them, the method of time or index separation of color-index signals is used. In this camera, a lined light filter, made of vertical, alternating red, blue, green and opaque bands, is installed in front of the light-sensitive surface of the camera tube (Fig. 5.13).

In scanning of the potential relief at the output of the camera tube of the camera being considered, a complex video signal appears, formed by triads of alternating pulsed signals of the three color-indexed images, separated by index signals, the level of which is constant and equal to the black level.

These index signals are extracted by the amplitude selection method, are passed through the corresponding delay lines and are used for alternate triggering of three gated amplifier cascades, /237 forming video signals of the three color-indexed images (Fig. 5.14).

Practical achievement of a color camera with time scanning of color-index signals involves a number of difficulties and limitations.

We will not dwell on those of them, which are connected to the technology of manufacture of the multicolor lined filter, camera tube operation and color-index signal separation devices, since all of these problems can be solved, by one method or another. We consider only those deficiencies, on which the possibility of using single-tube color cameras with time scanning of signals aboard a spacecraft depends.

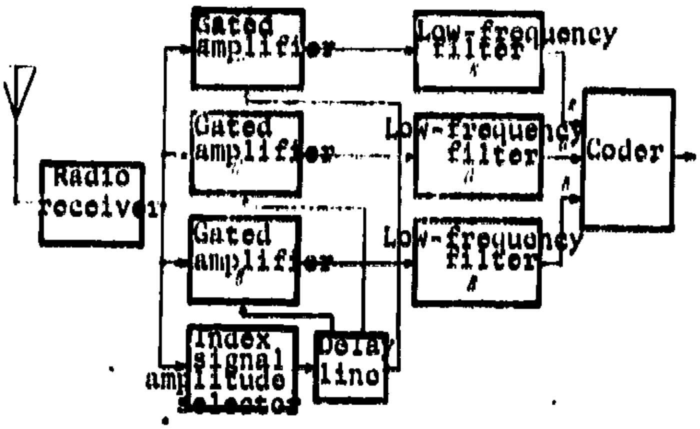


Fig. 5.14. Simplified structural diagram of SCTVS ground equipment, using color television camera with time scanning of signals.

One of the principal deficiencies is low resolution, fixed by the number of groups of color strips of the light filter, which decreases in the active section of the line. We designate the length of the operating section of the photoconducting layer of the camera tube by $l_ф$, the width of one strip of the lined color filter by Δl, the gap between strips by a (Fig. 5.13) and the number of color strips in one group of them by n, and we determine the horizontal resolution of a single-tube color camera, with frequency scanning of signals, by the formula

$$\nu = \frac{l_ф}{(\Delta l + a)n}. \qquad (5.1)$$

If it is considered that, practically, a color filter strip width Δl less than 20 μ cannot be obtained, that the gap between strips must be on the order of 5 μ and that, for a regular 1-inch camera tube $l_ф \approx 12.6$ mm, for the case being considered, we obtain ($n = 4$) $\nu = 126$ elements per line.

For the purpose of increasing resolution of a single-tube color camera, with time scanning of signals, a special camera tube of the "trinikon" type was developed in Japan; it forms index signals by purely electronic methods, without index strips in the lined light filter [113]. Owing to this innovation, as well as because of the fact that the length of the operating section of the photoconducting layer in the new tube is increased to 14 mm, the horizontal definition of the camera has been increased to 200 elements, which, of course, is insufficient for the majority of problems to be solved in space. /238

Another significant deficiency of the color camera version being considered is that, in it, all information on the color of the image is transmitted by means of short pulses, the number of which is four times greater than the number of elements resolvable during the time for scanning one line.

At those values, of which we spoke above, the video signal frequency band at the camera output exceeds 5 MHz. Correspondingly, a wide-band radio channel is required for transmission of these signals.

It should also be noted that, for a color television camera with frequency scanning, made of one camera tube, high sensitivity cannot be provided. This is mainly connected with the fact that only one fourth of the light flux reflected from the object being transmitted will be used for formation of color-indexed image signals in it. Moreover, because of the fine structure of the lined light filter, the camera tube will operate on a drop in the aperture characteristic, in that section of it, in which the intensity modulation will be 30-40%, in the best case.

As is evident from what has been said, a single-tube color television camera with time scanning of the color-index signals, from the point of view of its use aboard a spacecraft, cannot be considered to be promising.

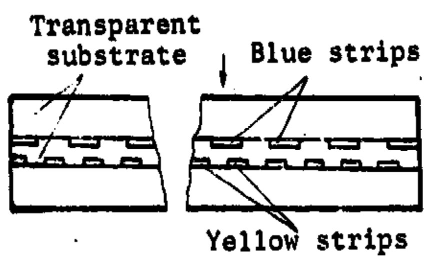


Fig. 5.15. Structure of lined light filter of color television camera with frequency scanning.

In color reporting units, in applied television and in recording color images on everyday videotape recorders, single-tube color television cameras with frequency scanning of the color-index signals are the most widely used. In these cameras, two-layer, fine-structured, lined light-divider light filters are installed in front of the light-sensitive surface of the camera tube, in the path of the light beams. The first layer of this light filter is formed by alternating vertical yellow and /239
transparent strips of equal width, produced on a transparent substrate, by photoetching of the corresponding dichroic coating. In the second layer, the alternating blue and transparent strips are wider than in the first layer (Fig. 5.15).

The two-layer, lined light filter produced in this manner is transparent to green rays.

The red rays pass only through the transparent strips of the first layer. The blue ones can pass through the transparent strips of the second layer without hindrance.

As a result of use of the light filter described above, a complex signal will be obtained at the camera tube output, which can be represented by the following expression:

$$E_s = (E_G + 0{,}5\,E_R + 0{,}5\,E_B) + 0{,}5\,E_R \cos\omega_R t + 0{,}5\,E_B \cos\omega_B t. \qquad (5.2)$$

The low-frequency components of the red (E_R), green (E_G) and blue (E_B) light-indexed images are included in the first term of this expression, and it can be extracted from the complete signal, by means of a low-frequency filter. The second and third terms of expression (5.2) are the high-frequency components, the amplitude-modulated signals of the red and blue color-indexed images, and they can be extracted, by means of band filters (Fig. 5.16). After this, by means of amplitude detectors and a simple matrix scheme, it is quite simple to obtain the required video signals of the three color-indexed images from the resulting signals, and to use them for forming a standard color television broadcasting system signal (Fig. 5.17).

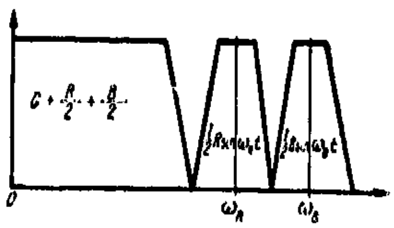


Fig. 5.16. Frequency characteristics of filters used for extraction of components of signal of color television camera with frequency scanning.

In the single-tube camera version with frequency separation of signals, the resolution depends directly on the structure of the lined light filter, which determines the values of the modulated subcarrier frequencies.

Each of the two subcarrier frequencies (f_{sR} and f_{sB}) can be calculated by using the expression

$$f_s = \frac{l_\phi F_{line}}{2\Delta l(1-\tau_r)}, \qquad (5.3)$$

where l_ϕ is the length of the working section of the camera tube photoconducting layer; Δl is the width of one strip of the lined light filter; F_{line} is the line scanning frequency; and τ_r is the duration of the return motion in percent. Assuming, as in the preceding version of the camera with signal time division, the minimum achievable width of a light filter strip /240

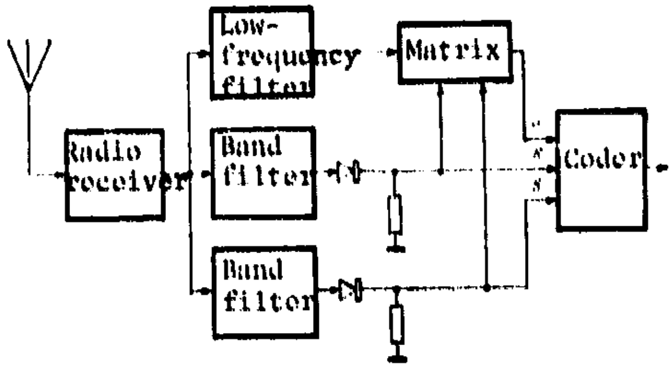


Fig. 5.17. Simplified structural diagram of SCTVS ground equipment, in the case of use of television camera with time division.

$A1 = 23\ \mu$, $l_\phi = 12.6$ mm and $\tau_p = 15\%$, we obtain the value of the higher modulated subcarrier signals of the blue image, with a frequency $f_{sB} = 5.1$ MHz. With this value of f_{sB}, the definition of the color image, depending on the green image signal frequency band E_G, will correspond approximately to 2.8 MHz (Fig. 5.16).

The analysis carried out shows that a single-tube camera with color-index signal frequency separation is distinguished advantageously from a camera with time division.

In a camera with frequency separation, in particular, it is easier to fabricate the lined light filter and considerably simpler to separate the color-indexed image signals. This camera, moreover, has a higher resolution, and it can have higher sensitivity.

However, the color information in this camera is located in the region of the highest frequencies of the video signal spectrum, and a wide-band radio channel is necessary for transmission of the signals. This circumstance significantly reduces the possibilities of use of a color camera with signal frequency separation in SCTVS.

In a number of reporting and other simplified color television cameras, field-sequential color-indexed image signals are formed at the output, with their subsequent conversion into simultaneous signals.

The principle of operation of this type of camera is based on reduction in the excess information contained in a standard color image signal. Practically, this is reduced to decreasing the color-indexed images transmitted per unit time to such a number of them, that smoothness of motion still is preserved. It is quite simple to make a sequential color television camera, by installing a rotating light filter, composed of alternating sectors of red, green and blue colors, in front of the light-sensitive surface of the camera tube. In this case, if the speed of this light filter is selected in such a manner that, /241
after scanning of each field of a transmitted image, one of the color sectors of the light filter is replac d by another one, color-indexed image signals will be obtainea at the camera output,

alternating through time intervals equal to the scanning period of the two fields of the raster.

In order to eliminate flickering in this method of color-index image signal formation, the signals of the filtered fields must be replaced by the signals of the preceding field, delayed by appropriate intervals of time, by means of a memory.

The method described of constructing single-tube color cameras permits a number of significant advantages to be obtained, which is especially important in use of such cameras in SCTVS.

The principal virtue of sequential cameras is that normal color-index image video signals can be obtained at their outputs. These signals can be transmitted over space radio channels with narrow transmission bands, since the limitation on their frequency spectrum will affect only the definit on of the color image, and it will not reflect at all on the corre tness of the color transmission.

An important virtue of the method of sequential transmission of color-index image signals also is the simplicity of accomplishing color correction of the color images transmitted, which is difficult to achieve in single-tube cameras with lined light filters. Single-tube cameras with sequential replacement of colors by fields are easy to bring into being, from the design and technicological viewpoints, and they can be made general-purpose, i.e., adaptable to solution of the most diverse problems under the conditions of space.

These advantages were put into practice in the space color television camera of the Westinghouse Company, which was used in executing the program of the American Apollo-10 manned spacecraft, which accomplished a soft landing on the surface of the moon.

In this camera, based on sequential forming of color-indexed image signals, the frequency of exchange of color filters was adopted as equal to the field frequency (60 Hz). In this case, ten complete color frames were transmitted per second. The images of the subjects transmitted were projected on the light-sensitive surface of the camera tube through a rotating light filter, made of alternating red, blue and green sectors. The sequential signals obtained at the camera output were transmitted to earth, by means of a 20 W radio transmitter, over a channel with a transmission band of 2 MHz (Fig. 5.18).

The simple-design, small-size onboard color camera of the Westinghouse Company had a total weight of 6.5 kg (Fig. 5.19). /242

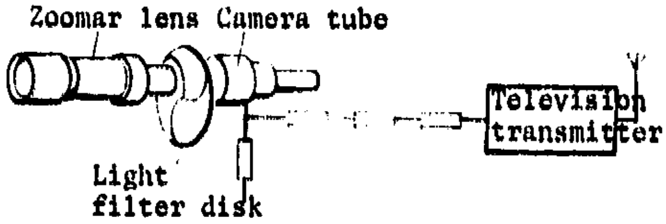


Fig. 5.18. Simplified structural diagram of onboard camera of Apollo-10 spacecraft.

Fig. 5.19. External appearance of Westinghouse Company color television camera.

The Apollo-10 spacecraft lunar camera had high sensitivity, and it could operate with a photoconducting layer illumination of 0.01 lux, providing a signal-noise ratio on the order of 35 dB. Such high parameters were achieved, as a result of use of a special, persistence-free "secon" type (SEC-vidicon) camera tube, adapted for operation under conditions of a wide temperature and illumination jump.

The sequential signals of the color-indexed images received by the ground stations passed through an automatic corrector of time errors, caused by the Doppler effect. After this, the signals were supplied to a standard converter, made in the form of a six-channel videotape recorder, one revolution of the disk of which corresponded to the transmission time of one field. In this device, the signals of each color-index image, following one after the other, were recorded in two of the six channels of the disk. After recording over an interval of time equal to the length of one field, the recorded signals were read out three times. Following this, the recorded information was erased, and the entire cycle of recording, readout and erasure began again. In this sequence of recording and readout, simultaneous signals of the three color-index images were obtained at the videotape recorder outputs. These signals were supplied to the input of the NTSC color television broadcasting system coder (Fig. 5.20).

The sequential color television camera discussed above was /243
used in the moon flights of the Apollo-11, Apollo-12 and Apollo-14 spacecraft [114].

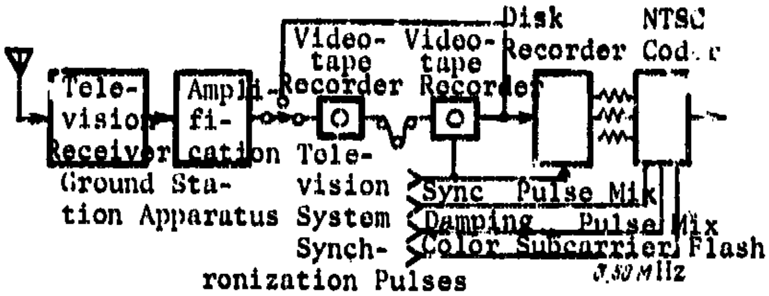


Fig. 5.20. Simplified structural diagram of ground equipment used in processing color signals transmitted from Apollo-10 spacecraft.

Subsequently, the RCA Company developed a more compact television camera, weighing 4.5 kg, in which a sensitive camera tube was used, with a "kremnikon" (SIT-vidicon) type silicon diode target, resistant to the action of direct sunlight [114].

The new version of onboard color camera was used in the flights of the Apollo-15 and Apollo-16 spacecraft, for transmission of color images from the command and lunar modules and from the surface of the moon.

REFERENCES

1. Televideniye (obshchiy kurs) [Television (general course)], P.V. Shmakov, ed., Moscow, "Svyaz'" Press, 1970, 540 pp. with illustrations.

2. Zvorykin, V.K. and D.A. Morton, Televideniye [Television], translated from the English, S.I. Katayev, ed., Moscow, Foreign Literature Publishing House, 1956, 780 pp. with illustrations.

3. Vozenkraft, Dzh. and I. Dzhekobs, Teoreticheskiye osnovy tekhniki svyazi [Theoretical foundations of communications technology], translated from the English, R.L. Dobrushin, ed., Moscow, "Mir" Press, 640 pp. with illustrations.

4. Kotel'nikov, V.A., Teoriya potentsial'noy pomekhoustoychivosti [Theory of potential freedom from interference], Moscow, Gosenergoizdat, 1956, 151 pp. with graphs.

5. Kolmogorov, A.N., Teoriya peredachi informatsii. Sessiya AN SSSR po nauchnym problemam avtomatizatsii proizvodstva 15-20 oktyabrya 1956 [Information transmission theory: Session of USSR Academy of Sciences on scientific problems of automation of production 15-20 October 1956], Moscow, Izd. AN SSSR, 1957.

6. Shennon, K., Raboty po teorii informatsii i kibernetike [Works on information theory and cybernetics], translated from the English by A.N. Kolmogorov, Moscow, Foreign Literature Publishing House, 1963, 829 pp. with diagrams.

7. Viner, N., Kibernetika ili upravleniye i svyaz' v zhivotnom i mashine [Cybernetics or control and communications in animal and machine], translated from the English by I.V. Solov'yev, G.N. Povarov, ed., Moscow, "Sovetskoye radio" Press, 1968, 215 pp. with diagrams.

8. Rose, A., "Relative sensitivities of television pickup /244
tube, photographic film and the human eye," Proc. IRE 30, 293-300 (1942).

9. Khadson, R., Infrakrasnyye sistemy [Infrared systems], translated from the English by Ya.B. Gerchikov, Moscow, "Mir" Press, 1972, 534 pp. with illustrations.

10. Valik, I.I. and L.I. Khromov, "Changes in value of ratio of signal to fluctuation interference in television camera tubes," in the collection Tekhnika televideniya [Television technology], Gosenergoizdat, 1956, No. 19, pp. 16-29.

11. Boerio, A.H., R.R. Beyer, and G.W. Goetre, "The SEC target. Advances in electronics and electron physics," Photoelectronic image devices, New York, Academic Press, Vol. 22A, 1966, pp. 229-239.

12. Valik, I.L., "Method of increasing sensitivity of a system with storage tubes," Ofitsial'nyy byulleten' izobreteniy, No. 10 (1961).

13. Garb, M.G. and V.M. Sigalov, Sinkhronizatsiya v televizionnoy tekhnike [Synchronization in television technology], Moscow, "Svyaz'" Press, 1964, 216 pp. with illustrations, one line diagram.

14. Krivosheyev, M.I., Osnovy televizionnykh izmereniy [Foundations of television measurements], Moscow, "Svyaz'" Press, 1964, 592 pp. with illustrations.

15. Tsukkerman, I.I., Preobrazovaniya elektronnykh izobrazheniy [Transformation of electronic images], Leningrad, "Energiya" Press, 1972, 748 pp. with diagrams.

16. Bordukov, G.S., V.I. Resin, and L.I. Khromov, "Effect of picture tube frequency distortions on television image quality," Tekhnika kino i televideniya, No. 11, 15-20 (1966).

17. Braude, G.V., Korrektsiya televizionnykh i impul'snykh signalov [Correction of television and pulse signals], Moscow, "Svyaz'" Press, 1967, 246 pp. with diagrams.

18. Khartli, R., "Information transmission," in the collection of articles Teoriya informatsii [Information theory], Moscow, Fizmatgiz, 1959.

19. O'Heyl, E., Vvedeniye v statisticheskuyu optiku [Introduction to statistical optics], Moscow, "Mir" Press, 1966, 254 pp. with illustrations.

20. Slyusarev, G.G., O vozmozhnom i nevozmozhnom v optike [The possible and the impossible in optics], Moscow, Fizmatgiz, 1960, 190 pp. with illustrations, one line drawing.

21. Ryftin, Ya.A., Televizionnaya sistema. Teoriya [Television system: Theory], Moscow, "Sovetskoye radio" Press, 1967, 271 pp. with illustrations.

22. Coltman, J.M. and A.E. Anderson, "Noise limitation to resolving power in electronic imaging," Proc. IRE 48/5, 858-865 (1960).

23. Khalfin, A.M., "Resolution of television systems," Radiotekhnika, No. 11, 45-48 (1961).

24. Krasil'nikov, N.N., Pomekhoustoychivost' televizionnykh ustroystv. [Interference stability of television apparatus], Moscow/Leningrad, Gosenergoizdat, 1961, 340 pp.

25. VanVleck, D. Middlton, "The spectrum of clipped noise," Proc. IEEE 54/1, 5-231 (1966).

26. Yaglom, A.M., "Introduction to theory of stationary random functions," Uspekhi matematicheskikh nauk 7/5, 3-168 (1952).

27. Bunimovich, V.I., Fluktuatsionnyye protsessy v radiopriyemnykh ustroystvakh [Fluctuation processes in radio receivers], Moscow, "Sovetskoye radio" Press, 1951, 360 pp. with diagrams.

28. Khromov, L.I. and V.I. Resin, "Noise injury to a video signal in television," Radiotekhnika, No. 12 (1967).

29. Katayev, S.I., Generatory impul'sov televizionnoy razvertki [Television scanning pulse generators], Moscow, Gosenergoizdat, 1951, 420 pp. with diagrams.

30. Gershberg, A.Ye., Peredayushchiye televizionnyye trubki, ispol'zuyushchiye vnutrenniy fotoeffekt [Television camera tubes using the internal photoeffect], Moscow, "Energiya" Press, 1964, 680 pp. with diagrams.

31. GOST 7845-55. Televideniye cherno-beloye. Osnovnyye parametry sistemi televizionnogo veshchaniya [All-Union State Standard 7845-55. Black-white television: Basic parameters of television broadcasting system], Moscow, 1956.

32. Lebedev, D.S. and I.I. Tsukkerman, Televideniye i teoriya informatsii [Television and information theory], Moscow/ /Leningrad, "Energiya" Press, 1965, 380 pp. with diagrams.

33. Khromov, L.I., "Effect of noise on accuracy of reception of continuous signals," Report to XXI Scientific-Technical Conference of A.S. Popov Scientific and Technical Department of Radio and Electronics, 19 April 1966 in Leningrad. /245

34. Khromov, L.I. and V.I. Resin, "Synthesis of optimum television systems," Tekhnika kino i televideniya, No. 4, 7-11 (1966).

35. Brok, G.K., Fizicheskiye osnovy aerofotografii [Physical bases of aerial photography], translated from the English, G.A. Istomin, ed., Geodeizdat, 1958, 299 pp. with diagrams and 16 line drawings.

36. Nyquist, H., "Certain factors affecting telegraph speed," Bell System Technical Journal 3/2, 324 (1924).

37. Khromov, L.I., "Remarks on the semantics of messages perceived by man," Voprosy radioelektroniki, seriya IX (Tekhnika televideniya) [Problems of radio electronics, Series IX, Television technology], Issue 3, 1964, p. 80.

38. Middlton, D., Vvedeniye v staticheskuyu teoriyu svyazi [Introduction to statistical theory of communications], translated from the English, Moscow, "Sovetskoye radio" Press, Vol. 1, 1961; Vol. 2, 1962.

39. Khromov, L.I., "Characteristics of optimum reception theory," Voprosy radioelektroniki, seriya "Tekhnika televideniya" [Problems of radio electronics, "Television technology" series], Issue 1, 1972.

40. Litvinchuk, L.A. and L.I. Khromov, "Principles of multi-element image energy storage in television and radar," ibid., Issue 5, 1970, p. 14.

41. Litvinchuk, L.A. and L.I. Khromov, "Effect of coding of continuous messages on potential resolution," ibid., Issue 4, 1971, p. 16.

42. Khurgin, Ya.I. and V.P. Yakovlev, Finitnyye funktsii v fizike i tekhnike [Finite functions in physics and technology], Moscow, "Nauka" Press, 1971, 364 pp. with illustrations.

43. Davenport, V.B. and V.L. Rut, Vvedeniye v teoriyu sluchaynykh signalov i shumov [Introduction to theory of random signals and noise], Moscow, Foreign Literature Publishing House, 1960, 468 pp. with diagrams.

44. Kotel'nikov, V.A., O propusknoy sposobnosti "efira" i provoloki v elektrosvyazi [Throughput capability of the "ether" and wires in electrical communications], RKKA Communications Administration, ed., 1933, 19 pp. with diagrams.

45. Vaynshteyn, L.A. and V.D. Zubakov, Vydeleniye signalov na fone sluchaynykh pomekh [Signal extraction on a background of random noise], Moscow, "Sovetskoye radio" Press, 1960, 447 pp. with diagrams.

46. Andrade, Zh.L., E. Sil'va, and Zh. Loshak, Polya, chastitsy, kvanty [Fields, particles, quanta], translated from the French, Moscow, "Nauka" Press, 1972, 189 pp. with illustrations.

47. Katayev, S.I. and L.I. Khromov, "Generalized critera for evaluation of image quality," Tekhnika kino i televideniya, No. 4, 17, 18 (1962); and No. 3, 63 (1964).

48. Zheleznov, N.A., Nekotoryye voprosy teorii informatsionnykh elektricheskikh sistem [Problems in theory of electrical information systems], Leningrad, LKVVIA, 1960, 155 pp.

49. Khromov, L.I., "Method of calculation of potential resolution," Tekhnika kino i televideniya, No. 2, 53 (1971).

50. Khelstrom, K., Statisticheskaya teoriya obnaruzheniya signalov [Statistical theory of signal detection], translated from the English by G.Yu. Kobzarev, Moscow, Foreign Literature Publishing House, 1963, 431 pp. with diagrams.

51. Vudvord, F.M., Teoriya veroyatnostey i teoriya informatsii s primeneniyami v radiolokatsii [Probability theory and information theory, with applications to radar], translated from the English by S.I. Borovitskiy, Moscow, "Sovetskoye radio" Press, 1955, 128 pp. with diagrams.

52. Sovremennaya radiolokatsiya [Modern radar], translated from the English, Moscow, "Sovetskoye radio" Press, 1969, 704 pp. with illustrations.

53. Luizov, A.V., Inertsiya zreniya [Visual persistence], Moscow, Oborongiz, 1961, 248 pp. with illustrations.

54. Nyquist, H., "Certain topics in telegraph transmission theory," Transactions AIEE 47, 617 (1928).

55. Reley, Dzh.V., Volnovaya teoriya sveta [Wave theory of light], Moscow/Leningrad, Gostekhizdat, 1940, 208 pp. with diagrams.

56. Khromov, L.I., "Basic assumptions of spectral-information method of calculation of television system resolution," Voprosy radioelektroniki, seriya "Tekhnika televideniya" [Problems of radio electronics, "Television technology" series], Issue 2, 1968, p. 16.

57. Khromov, L.I. and V.I. Resin, "Generalized frequency criteria of evaluation of image reproduction accuracy," Tekhnika kino i televideniya, No. 4, 39-44 (1963).

58. Khromov, L.I. and V.I. Resin, "Application of information theory to television system planning," Tekhnika kino i televideniya, No. 3, 35-43 (1964). /246

59. Khromov, L.I. and V.I. Resin, "Determination and calculation of pulse resolution in television," Tekhnika kino i televideniya, No. 4 (1967).

60. Resin, V.I., "Connection between calculated and subjective estimates of resolution," Tekhnika kino i televideniya, No. 10, 57 (1970).

61. Katayev, S.I., "Possibility of television picture transmission by means of a narrow frequency band," Radiotekhnika, no. 2, 71-80 (1937).

62. Osnovy televideniya. Kurs [Foundations of television: Course], Prof. S.I. Katayev, ed., Moscow, Svyaz'izdat, 1940, 336 pp. with diagrams and illustrations.

63. Bordukov, G.S. et al., "Television systems with adjustable parameters," Tekhnika kino i televideniya, No. 4, 50 (1971).

64. Khromov, L.I. et al., "A method of television image transmission," USSR author's certificate on invention No. 311423, 2 December 1969, published 9 August 1971.

65. Viner, N., Kibernetika i obshchestvo [Cybernetics and society], translated from the English by Ye.G. Panfilov, Moscow, Foreign Literature Publishing House, 1953, 200 pp.

66. Khromov, L.I., Preobrazovaniye signala pri nalichii fluktuatsionnykh pomekh v uzkopolosnykh peredayushchikh televizionnykh ustroystvakh [Signal conversion in the presence of fluctuation interference in narrow-band television transmitters], Candidate's dissertation, LIAP, 1958.

67. Khromov, L.I., "Some methods of image transmission by means of a narrow frequency band," in the collection Tekhnika televideniya [Television technology], Gosenergoizdat, No. 29, 1958, pp. 82-102.

68. Valik, I.L. and L.I. Khromov, "Narrow-band, slow-scan television systems," Tekhnika kino i televideniya, No. 12, 19-24, (1958).

69. Valik, I.L. and L.I. Khromov, "New type of television system," Radiotekhnika 16/2, 74-78 (1961).

70. Khromov, L.I., "Effect of selecting field on signal in the supericonoscope," Radiotekhnika 14/11, 28-35 (1959).

71. Konchin, V.I. and L.I. Khromov, "Investigation of television storage device persistence," Radiotekhnika 20/9, 58-62 (1965).

72. Valik, I.L. and L.I. Khromov, "Possibility of use of television camera tubes for detection of faint optical images," ZhTF 29/7, 881-884 (1959).

73. Konchin, V.I., O.V. Goncharov, and L.I. Khromov, "Regulation of storage process in superorthicon television cameras," Tekhnika kino i televideniya, No. 1, 59-64 (1965).

74. Khromov, L.I., "Improvement of image quality in narrow-band cameras," Tekhnika kino i televideniya, No. 3, 22-26 (1960).

75. Konchin, V.I. and L.I. Khromov, "Collection of primary video information by means of slow-scan television devices," Radiotekhnika 21/5, 39-46 (1966).

76. Fantikov, O.I., "Construction of low-noise video amplifiers for narrow-band vidicon television systems," Voprosy radioelektroniki, seriya 'Tekhnika televideniya" [Problems of radio electronics, "Television technology" series], Issue 3, 1971, p. 87.

77. Kossov, G.Ya., "Investigation of frequency-contrast characteristics of various types of lenses used in television systems," Elektronnaya tekhnika, Seriya IV, (Elektronnoluchevyye i fotoelektrocheskiye pribory) [Electronic technology, Series IV, Electron-beam and photoelectric devices], Issue 3, 1967.

78. Fantikov, I.I. and G.V. Kuznetsova, "Increase in resolution of slow-scan systems," Tekhnika kino i televideniya, No. 12, 42 (1971).

79. Schade, O.H., "Electron optics and signal readout of high-definition return beam vidicon camera," RCA Review 31/1, 60 (1970).

80. Khromov, L.I. and V.I. Resin, "Video amplifier with automatic control of amplitude-frequency characteristics," USSR author's certificate on invention No. 284057, 10 April 1969, Byulleten' izobreteniy, No. 32 (1970). /247

81. Brigham, E.O., H.W. Smith, F.X. Bostick, and W.C. Duesterhoeft, "An iterative technique for determining inverse filters," IEEE Transactions on geoscience electronics GE-6/2, 86 (1968).

82. Feller, V., Vvedeniye v teoriyu veroyatnostey i yeye prilozheniya [Introduction to probability theory and its applications], Moscow, "Mir" Press, 1964, 636 pp. with diagrams.

83. Sushchev, G.A., "Sensitivity of television systems using camera tubes with charge storage," Voprosy radioelektroniki, seriya "Tekhnika televideniya" [Problems of radio electronics, "Television technology" series], Issue 1, 1972.

84. Lezin, Yu.S., Optimal'nyye fil'try i nakopiteli impul'snykh signalov [Optimum pulse signal filters and storage devices], Moscow, "Sovetskoye radio" Press, 1969, 580 pp.

85. Kleinhans, W.A., "Optimum spectral filtering for background-limited infrared systems," Journ. Opt. Soc. Amer. 55/1, 104 (1965).

86. Rosell, F.A., "Limiting resolution of low-light-level imaging sensors," Journ. Opt. Soc. Amer. 59/5, 539 (1969).

87. Krusser, B.V., V.I. Konchin, and R. Gaudulina, "Method of neutralization of residual charges of superorthicon targets," Ofitsial'nyy byulleten' izobreteniy, No. 1 (1960).

88. Valik, I.L., L.I. Khromov, and I.N. Shetalov, "Method of use of vidicon with long memory," Author's certificate on invention with priority from 3 January 1960, Byulleten' izobreteniy, No. 13, 32 (1966).

89. Knol', M. and B. Keyzan, Elektronnoluchevyye trubki s nakopleniyem zaryadov [Electron-beam tubes with charge storage], translated from the English, M.L. Veysben, ed., Gosenergoizdat, 1955, 160 pp. with diagrams.

90. Sevin, L.D., Polevyye tranzistory [Field-effect transistors], translated from the English by A.G. Korol'kov, Moscow, "Sovetskoye radio" Press, 1968, 181 pp. with illustrations.

91. Khatuntsev, A.I. et al., "Supplementary source of low-frequency noise in field-effect transistors," Elektronnaya tekhnika, seriya 1 (Poluprovodnikovyye pribory) [Electronic technology, Series 1, Semiconductor Devices], Issue 2, 1970, p. 149.

92. Gradshteyn, I.S. and I.P. Ruzhik, Tablitsy integralov, summ, ryadov i proizvedeniy [Tables of integrals, sums, series and derivatives], Moscow, "Nauka" Press, 1971.

93. Tayts, T.I., "Automatic parameter regulation (APR) of television system video amplifier loop," Voprosy radioelektroniki, seriya IX (Tekhnika televideniya) [Problems in radio electronics, Series 9, Television technology], Issue 2, 1962.

94. Tayts, T.I., "Efficiency of line-by-line systems of automatic parameter regulation of a video amplifier circuit," ibid., Issue 7, 1963.

95. Pervyye fotografii obratnoy storony Luny [First photographs of the back side of the moon], Moscow, Izd. AN SSSR, 1959, 35 pp. with illustrations.

96. Bratslavets, P.F., I.A. Rosselevich, and L.I. Khromov, Televideniye v osvoyenii kosmosa. Nauchno-tekhnicheskiy sbornik [Television in the mastery of space: Scientific-technical collection], Moscow, "Svyaz'" Press, 1971.

97. Gurov, V.A., Osnovy dal'novideniya [Foundations of foresight], Moscow, Radioizdat, 1936, 371 pp. with illustrations.

98. Selivanov, A.S. et al., "Phototelevision apparatus for space research," Tekhnika kino i televideniya, No. 7 (1969).

99. Lagutin, Yu.P., "Potential resolution of traveling beam television apparatus," Voprosy radioelektroniki, seriya IX (Tekhnika televideniya) [Problems in radio electronics, Series 9, Television technology], Issue 3, 1969.

100. Pervyye panoramy lunnoy poverkhnosti. Po materialam avtomaticheskoy stantsii "Luna-9" [The first panoramas of the lunar surface: From materials of the Luna-9 unmanned spacecraft], Moscow, "Nauka" Press, 1966, 103 pp. with illustrations and maps.

101. Selivanov, A.S. et al., "Panoramic television camera for unmanned lunar spacecraft," Tekhnika kino i televideniya, No. 1 (1968).

102. Selivanov, A.S. et al., "Panoramic survey television systems for second generation unmanned lunar spacecraft," Tekhnika kino i televideniya, No. 5, 43-46 (1972). /248

103. Barret, E.K., Pogoda iz kosmosa [The weather from space], Leningrad, Gidrometeoizdat, 1970.

104. Dennis, Le Groisette, "The scientific instruments on Surveyor," IEEE Trans. on Aerospace and Electronic System AES-5/1, 2-21 (1969).

105. Montgomery, D.R. and L.A. Adams, "Optics and the Mariner imaging instrument," Applied Optics 9/2, 277-278 (1970).

106. Aviation Week 88/19, 71, 73, 76, 79 (1968).

107. Suomi, V.E. and T.H. Von der Haar, "Geosynchronous meteorological satellite," Journal of Spacecraft and Rockets 6/3, 342-344 (1969).

108. Lytkin, B.I., "Method of television image synchronization," Byulleten' izobreteniy, No. 12, 141 (1964).

109. Katayev, S.I., V.G. Makoveyev, V.V. Smirnov, E.V. Dymnich, and G.A. Avanesov, "Experimental standard television signal converter," Tezisy dokladov XXII nauchnoy sessii NTORiE im. A.S. Popova [Summaries of reports of XXII scientific session of A.S. Popov Scientific and Technical Department of Radio and Electronics], Moscow, 1966.

110. Shmakov, P.V. et al., "Color television in space," Trudy uchebnykh institutov svyazi, Issue 39, 3 (1968).

111. "Air Force's secret laser scanner transmits its first color foto," Laser Focus 5/15, 22 (August 1969).

112. Bachmann, H. and H. Lung, "A color television camera for applied television," Feinwerktechnik 75/12, 484 (1971).

113. Electronics 44/4, 11E (1971).

114. Zazerskaya, V.I. and M.N. Tsaplin, "Television systems of the Apollo spacecraft," Tekhnika kino i televideniya, No. 12, 55 (1971).

115. Bratslavets, P.F., I.A. Rosselevich, and L.I. Khromov, Kosmicheskoye televideniye [Space television], Moscow, "Svyaz'" Press, 1967.